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Flight Technical Error for Category B Non-Precision Approaches and Missed Approaches Using Non-Differential GPS for Course Guidance

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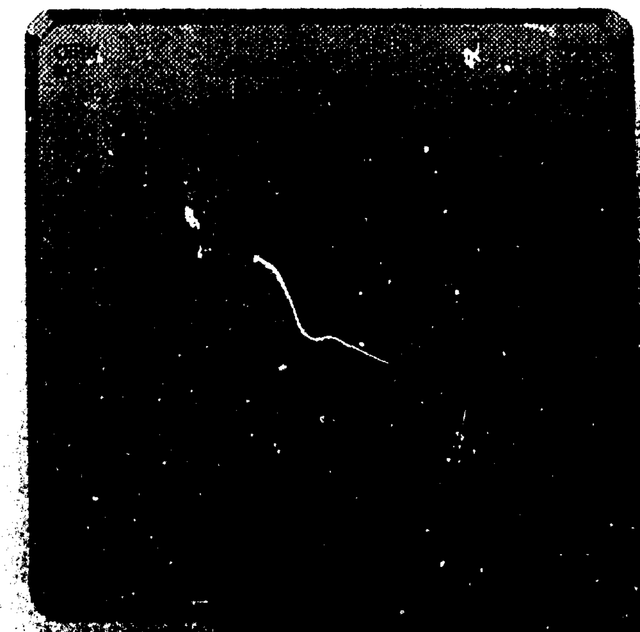

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Research and Special Programs Administration
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Cambridge, MA 02142

Final Report
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13. ABSTRACT (Maximum 200 words)

Twelve general aviation pilots flew a Beechcraft Baron on 93 non-precision instrument approaches using a non-differential GPS receiver modified to satisfy selected functional requirements specified in TSO-C129.

The purposes of the effort were to determine if the CDI sensitivity levels specified in the TSO were flyable by GA pilots and if flight technical error could be contained within trapezoids defined by TERPS criteria specified for approaches using off-site VORs.

Pilots rated the sensitivity levels flyable, and flight technical error was well within VOR TERPS limits. Pilot performance during missed approaches, and the use of GPS in the terminal area during IFR and VFR operations were identified as areas requiring additional research.

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PREFACE

This report documents and discusses the performance of twelve General Aviation Pilots who used Non-Differential GPS in a Beechcraft Baron to fly 93 Category B approaches defined by GPS waypoints. The research reported here was part of the FAA's GPS Overlay Project and provided the data required by the Agency to implement Phase I of the GPS satellite Operational Plan for Category B non-precision approaches.

The data collection and analysis procedures described herein were developed with and approved by the FAA's Satellite Operations Implementation Team. It should be noted, however, that although the analysis procedures described here were appropriate for the purposes of this study, additional work would be required to prepare the data for use in the development of GPS TERPS.

Financial support for the instrumentation of the aircraft and the preparation of this report was provided by ARD-210, the Human Performance Program in the Systems Technology Division of the FAA Research and Development Service. Financial support for the design of this research, collection of pilot performance data, and analysis of those data was provided by the GPS Program Office in the Research and Development Service.

The authors would like to thank Aero Club of New England for their support of this work and the twelve general aviation pilots who flew the data collection approaches. Thanks also go to Bob Disario for his assistance in the analysis of the flight technical error data collected in this study.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2 = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2 = 0.09 square meter (m_2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (1)
1 pint (pt) = 0.47 liter (1)
1 quart (qt) = 0.96 liter (1)
1 gallon (gal) = 3.8 liters (1)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliters (ml) = 0.03 fluid ounce (fl oz)
1 liter (1) = 2.1 pints (pt)
1 liter (1) = 1.06 quarts (qt)
1 liter (1) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0	1	2	3	4	5	6	7	8	9	10

CENTIMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ANOVA	analysis of variance
ATC	air traffic control
CDI	course deviation indicator
DME	distance measuring equipment
FAF	final approach fix
FTE	flight technical error
GPS	global positioning systems
HDOP	horizontal dilution of precision
HSI	horizontal situation indicator
IAF	initial approach fix
IF	intermediate fix
IMC	instrument meteorological conditions
LCD	liquid crystal display
MAP	missed approach point
MDA	minimum descent altitude
NAS	national airspace system
NDB	non-directional radio beacon
NOS	National Ocean Service
RNAV	area navigation
SA	selective availability
SP	safety pilot
TERPS	terminal instrument procedures
TSO	technical standard order
VFR	visual flight rules
VNTSC	Volpe National Transportation Systems Center
VOR	very high frequency omnidirectional range

1. INTRODUCTION

1.1 PURPOSE

This flight test program was conducted by the Volpe National Transportation Systems Center (Volpe Center) to support the FAA's Global Positioning System (GPS) Program Office in the early implementation of GPS navigation in the National Airspace System (NAS) and to support the Research and Development Services Cockpit Human Factors Program (ARD-210) in developing an understanding of the influence of instrument approach procedures on pilot performance. The Program office is interested in determining if the course deviation indicator (CDI) sensitivities specified in the technical standard order for GPS receivers (TSO C129) are flyable and will produce pilot tracking performance that is sufficiently accurate to permit GPS to be used for non-precision approaches currently designed for VHF Omnidirectional Range (VOR) and Nondirectional Radio Beacon (NDB) navigation. ARD-210 is interested in studying pilot performance in executing terminal area procedures to develop fundamental data for use in developing procedures that are safe and flyable.

This work was designed to determine the accuracy with which general aviation and commercial pilots may be expected to track the CDI driven by non-differential GPS while executing approach and missed approach procedures on a non-precision approach. Earlier work (Huntley et al., 1991), evaluating the influence of CDI sensitivity on Flight Technical Error (FTE) during Category A (0-90 Kts) approaches indicates that sensitivity levels above the usual 1.25 setting normally used for Area Navigation systems approaches are quite flyable and may yield significant reductions in FTE. It was shown that sensitivities as high as 0.30 nm for a full-scale deflection reduce FTE by as much as 30 percent without unacceptable increases in pilot workload. Low FTE coupled with the small system errors expected from GPS could permit the installation of instrument approaches in runways that do not now have them because of obstructions or other approaches nearby.

The technical standard order for GPS receivers (TSO C129) specifies that 0.30 nm be used for non-precision approaches and that the sensitivity be changed from 1.0 nm, used for terminal operations, to 0.30 nm prior to the final approach fix (FAF).

The objectives of the study were the following:

- To determine whether the CDI sensitivities specified in TSO C129 for non-precision approaches are flyable by low time general aviation pilots in a Category B aircraft.

- To verify that terminal instrument procedures (TERPS) currently used for VOR, VOR distance measuring equipment (VOR DME), and NDB approaches are sufficiently conservative to be used for GPS non-precision approaches. If this is the case, early implementation of GPS could be facilitated by allowing pilots to use GPS for most non-precision approaches before special terminal procedures are designed specifically for GPS. Localizer approaches are currently excluded from this early implementation strategy.

- To determine the accuracy with which general aviation pilots can be expected to follow positive course guidance during a missed approach using the terminal area CDI sensitivity setting of 1.0 nm.

2. TECHNICAL APPROACH SUMMARY

Twelve commercial and general aviation pilots were selected on the basis of their flight experience to form two subgroups of test pilots. Six low- and six high-time pilots flew a GPS-equipped Beechcraft Baron through standard non-precision instrument approach and missed approach at a non-towered airport. The instrument approach procedure was totally defined by a series of GPS waypoints that described one of the more difficult procedures currently permitted by TERPS.

The test pilots were trained in the use of the GPS receiver as an instrument flight course guidance device and flew one practice GPS approach. The approach procedure, depicted in standard NOS approach chart format, was available for study and reference prior to and during all approaches. The test flights were conducted with a crew of three: the test pilot, a safety pilot, and a data collection technician.

Each pilot flew eight test approaches. Flight technical error, distance to waypoint, and ground speed were recorded during each approach. Estimates of pilot workload were based on pilot reports, using a modified Cooper-Harper technique and a mental comparison with VOR and NDB approaches.

Data on pilot tracking performance on 93 approaches were analyzed to determine maximum FTE, mean FTE, and 95 percent probability FTE values for selected straight segments of the downwind, intermediate, and final approach courses; the missed approach course; at every half mile point on the final approach course; and also at the IAF, FAF and MAP. Aircraft position error was determined by summing the FTE measured in the aircraft with an assumed GPS position error of 100 meters.

3. DETAILED TECHNICAL APPROACH

3.1 TEST AIRCRAFT

A BE55 (Beechcraft Baron) was selected as representative of Category B aircraft that might typically be used in general aviation operations to uncontrolled airfields. This twin engine aircraft cruises at 180 knots, has an approach speed of 100 knots, and is complex enough in single pilot operations to provide a relatively high workload environment from which to develop conservative estimates of pilot performance capabilities under the terminal area conditions of interest.

Instrument Panel Layout

The instrument panel layout in Figure 1 represents a typical, but not ideal organization of cockpit instruments. The aircraft is equipped with a Century Systems NSD-360 Horizontal Situation Indicator (HSI), depicted in Figure 2, located directly in front of the pilot. A King CDI is located beneath the HSI and can be driven by either VOR receiver. A smaller CDI (MD 40-08, Mid-Continent Instrument Co.) for use with the GPS was mounted to the right of the King CDI and directly below the VSI. As required by TSO C60b, this GPS CDI display includes warning and annunciator lights to alert the pilot to changes in signal quality or an approaching waypoint.

GPS Receiver

A Northstar M2 GPS receiver was used for guidance. This receiver accommodates over 200 user waypoints in a user data base, has automatic sequencing in the flight plan mode, and provides position updates once per second. Operating controls and the alphanumeric liquid crystal display (LCD) are located on the approximately two- by six-inch face of the unit.

The results of this testing were, to some unknown extent, probably dependent on the receiver used for guidance. The attention and effort required by the pilot to operate the receiver may affect the attention remaining to the pilot for the airplane and course tracking. Also, different receivers may process the incoming GPS signal in ways that have different effects upon CDI movement and responsiveness.

The receiver is mounted halfway up the NAV/COM stack on the far side of the engine mixture controls. From the pilots' operational point of view, this is not an ideal location for the unit. The pilots must see and reach around the power controls in order to use it, and they must refer to this display for distance-to-waypoint information during the approach. It is, however, a typical location for Loran/GPS receivers in general aviation aircraft.

During testing, the GPS receiver was programmed with a flight plan that sequenced automatically from segment to segment, as the test pilot flew through the approach procedure. The display on the receiver showed the name of the upcoming waypoint, and the distance and bearing to that waypoint while in the approach mode. A rectilinear CDI is also on the receiver display but was shielded from the pilots' view. Normally, crosstrack distance in digits may be selected if the pilots want it. The pilots were not permitted to use this option

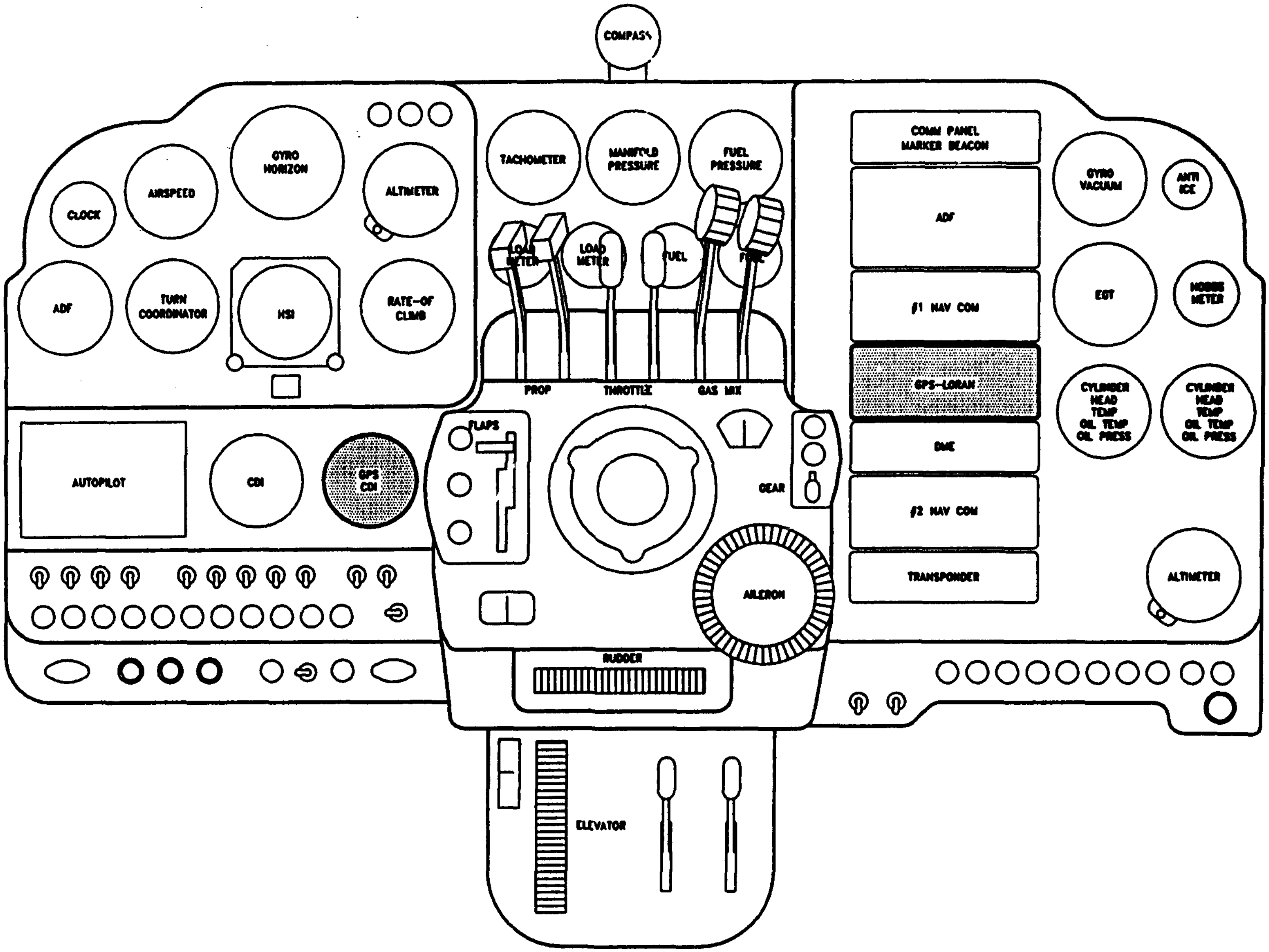

Figure 1. Instrument panel layout

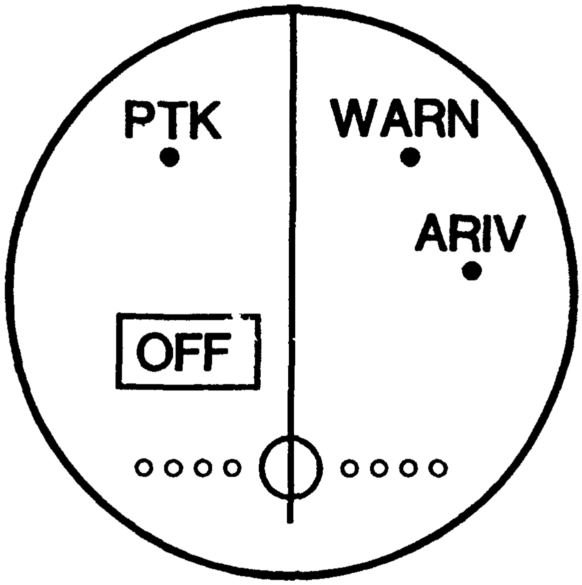

Figure 2. Century Systems NSD-360 horizontal situation indicator

during the test flights. During all flights the remote GPS CDI was used by the pilots for guidance.

For purposes of the present test, the M2 was modified to provide a CDI sensitivity of 1 nm full scale during the initial approach segment of the approach and to switch automatically to 0.3 nm full scale two miles from the FAF while on the intermediate segment. This switch in sensitivity was immediate rather than gradual.

3.2 FLIGHT TASK VARIABLES

CDI Sensitivity

CDI sensitivity was 1.0 nm (full scale) for the initial segment, a subsequent 120 degree turn, and most of the intermediate segment of the approach procedure. It switched automatically to 0.30 nm (full scale), 2 nm before the final approach fix and back to 1.0 nm at the missed approach point.

IMC Simulation

Throughout the testing, pilots were hooded as they flew the approach and missed approach. A standard hood or foggles were used to simulate instrument meteorological conditions (IMC).

In order to keep the pilot prepared for a landing, a landing was required on one out of every four approaches. The pilot was informed at the minimum descent altitude (MDA) whether a particular approach would terminate in a landing.

3.3 STANDARD DATA SET

The data collected on each approach included the following:

- Flight Technical Error

  FTE was recorded continuously and automatically, directly from the CDI referenced by the pilot during the approach procedure. When the needle went to the limit, FTE data was recorded from the GPS receiver.

- Aircraft Position Error

  Worst case (95%) position error was assumed and estimated by adding 0.054 mile (100 meters) to the FTE recorded in the airplane.

- HDOP and Position Solution Error

  The horizontal dilution of precision (HDOP) was recorded from the receiver once during each approach. Approaches were flown for data only when HDOP was 2 or better. Average HDOP for testing was 1.29 with a range of 1.0 to 2.0.

  Position errors in the GPS solution caused by selective availability (SA) were recorded during each approach but they have not been included in the data analysis. Error variation for a typical 24 hour period and a sample approach are described in this report. Position error observations and recordings were made at the Volpe National Transportation Systems Center (Volpe Center) in Cambridge while the approaches were flown at the Gardner Airport. Cambridge is located approximately 48 nm from Gardner.

  All data that were collected automatically on the aircraft were recorded in flight on 3.5 inch floppy and internal "hard" discs by an on-board Halikan minicomputer.

  The aircraft was equipped and staffed identically for each data collection flight. The Baron is designed to accommodate six people. The rear two seats were removed and an instrumentation package was secured in the baggage compartment. This data collection instrumentation weighed approximately 30 pounds and was portable. It was removed from the aircraft at the end of each test day.

- Pilot Workload

  Pilot estimates of directly perceived workload and relative workload as compared with VOR and NDB approaches were recorded. A modified version of the Cooper-Harper scale

was used for one estimate of the pilot workload. Research indicates that the most reliable and valid measure of pilot workload is the pilot's own subjective estimate. The most used and best researched procedures for systematically getting such estimates are variations of the Cooper-Harper Scale. This scale was originally developed to obtain pilots' estimates of aircraft handling. It requires the pilot to make a set of consecutive judgments on task difficulty and a single score on a ten-point scale is derived from these. The Volpe Center variation of the scale is illustrated in Figure 3. The test pilot was asked to make a workload judgment on downwind following the fourth in each set of four approaches flown.

During a debriefing session following each set of approaches, each pilot was asked to compare the difficulty of GPS approaches with those defined by VORs and NDBs. These comparisons were made using the scale shown in Figures 4 and 5. This scale is a variation of one developed by Boeing Aircraft for use in comparing immediately experienced workload in a new aircraft with that of another recently flown aircraft.

3.4 RESEARCH SITE

The research was conducted using two separate airports: Minuteman Airfield, and Gardner Airfield.

Minuteman Airfield is a small, private field located 25 miles northwest of Boston in Stow, Massachusetts. This facility includes a small restaurant, a 2770 foot runway, office space, fuel, and maintenance support. The Baron is leased from an FBO resident at this airport and is permanently based there.

Gardner Airport is a non-towered municipal airport that is located approximately 22 miles northwest of Stow. The runway at Gardner is 3000 feet long and is rarely busy during the week. There is a VOR-A instrument approach into Gardner. Prototype GPS instrument approaches into Gardner have been established and no difficulty has been experienced in flying these approaches at this location. All data collection flights were flown at Gardner.

3.5 TEST SUBJECTS

Our pilot pool included general aviation pilots who answered an advertisement in a local aviation newsletter or a survey of members of the Aero Club of New England. All subjects were current in the Baron and had a current instrument rating. The suitability of the volunteers as test pilots for the study was determined from observations of pilot performance during practice approaches flown at Gardner and flight experience as recorded in pilot logbooks.

Two groups of pilots were used in this study. The low-time group consisted of pilots who flew primarily for pleasure, had their instrument ticket, were current in a Baron, had less than 500 hours total time, and less than 100 hours in a Baron.

The high-time pilots were instrument rated, were current in a Baron, had at least 1000 hours total time and 500 hours in multi-engine aircraft.

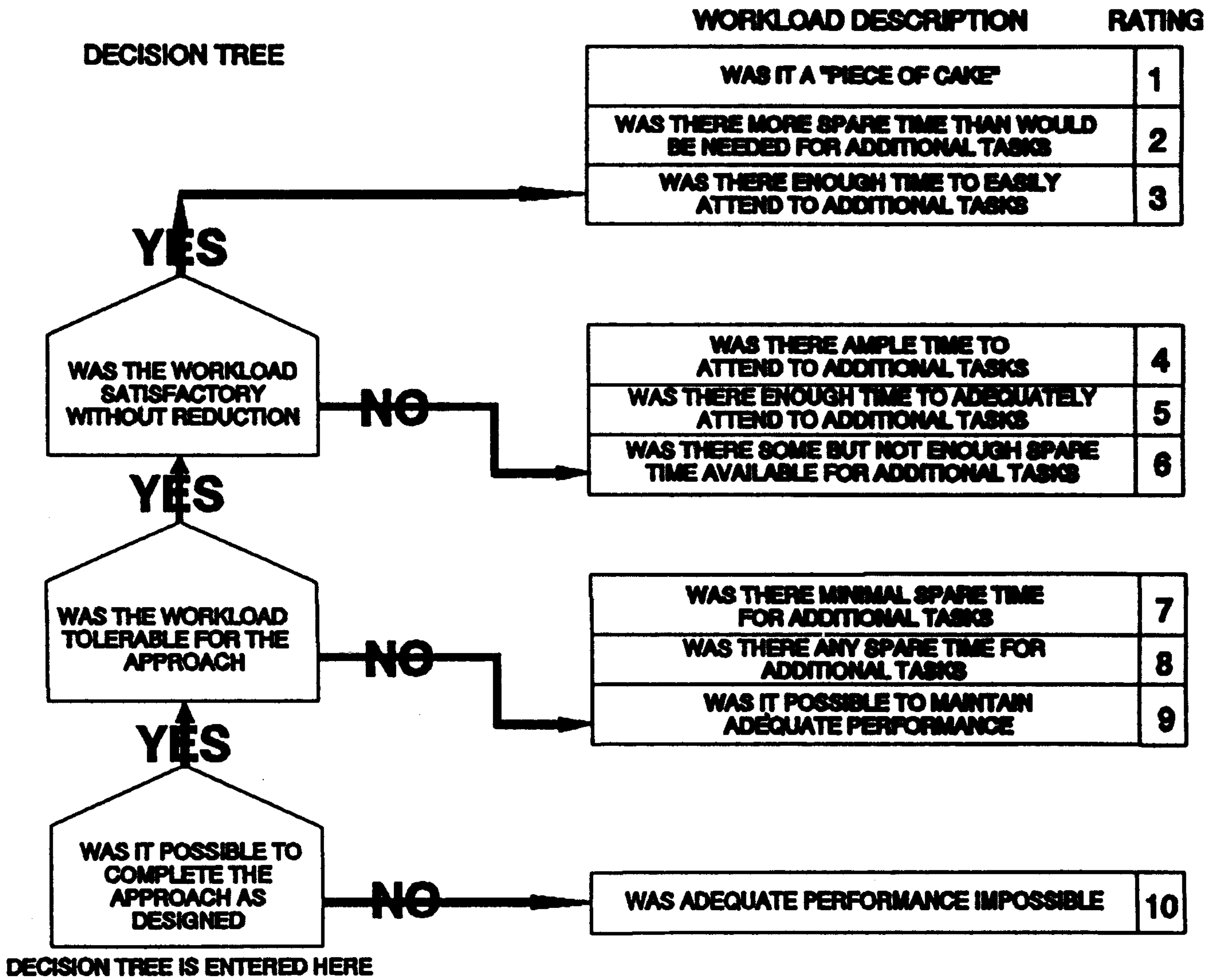

Figure 3. Decision tree

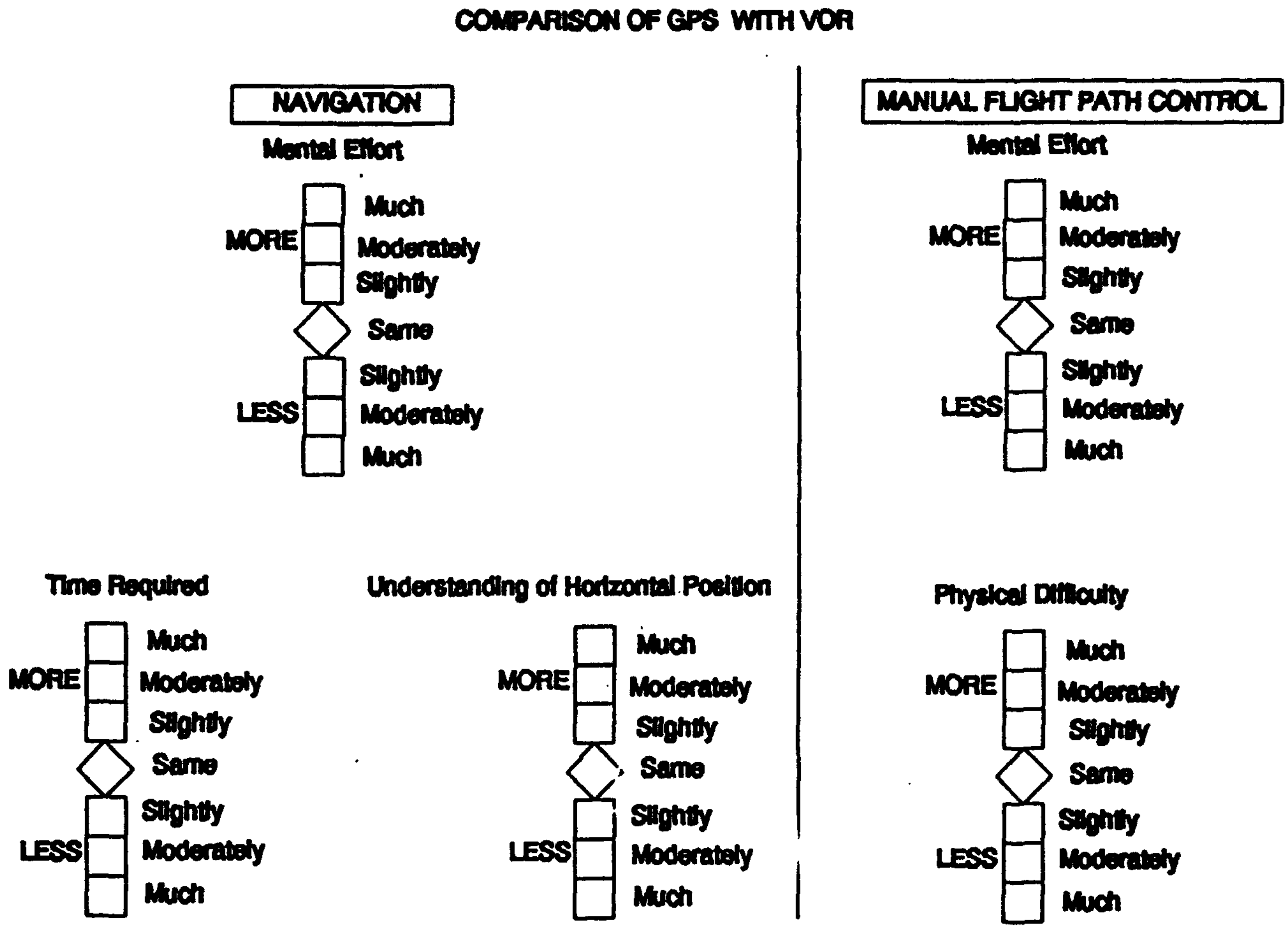

Figure 4. Comparison of GPS with VOR

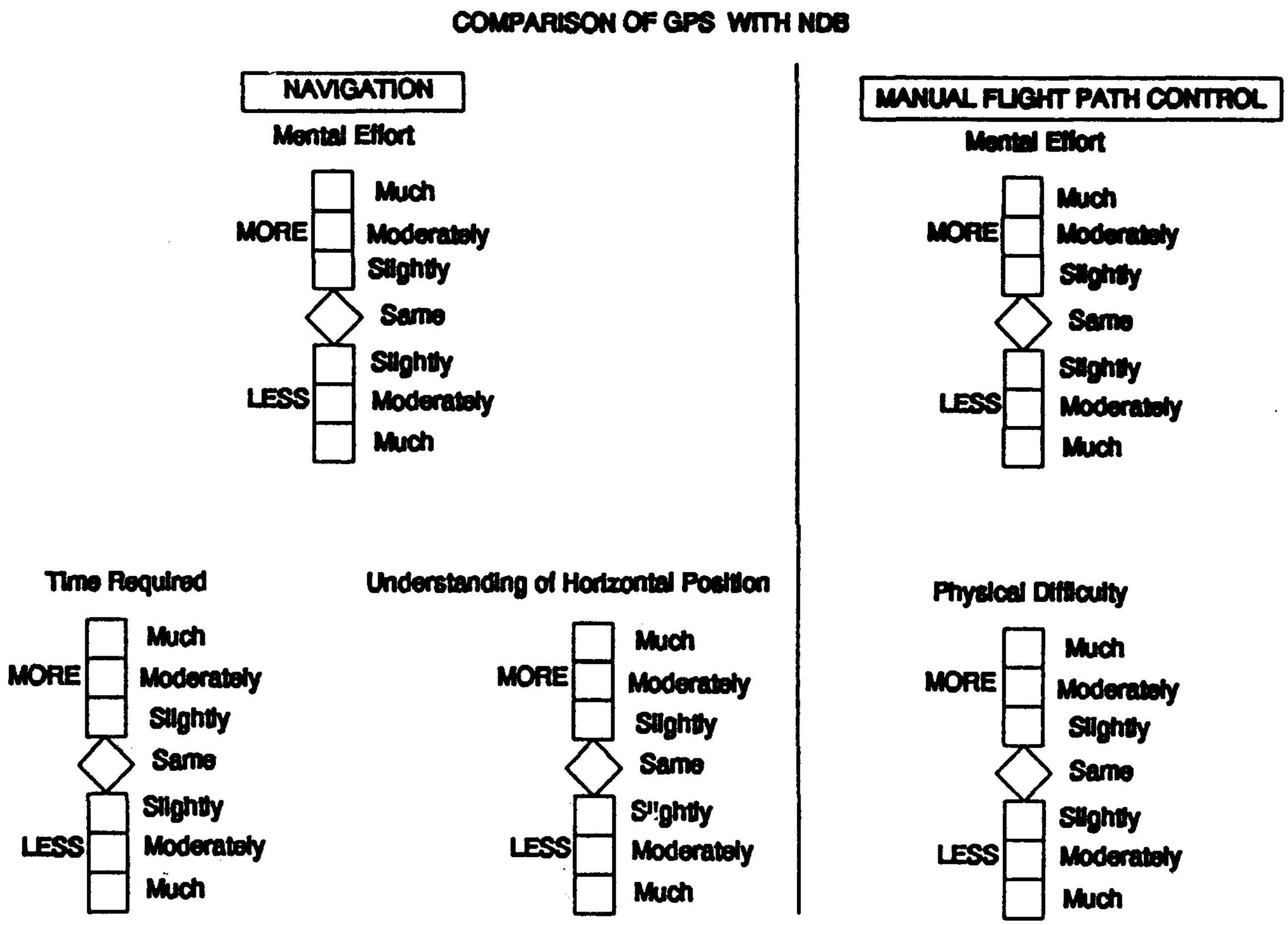

Figure 5. Comparison of GPS with NDB

3.6 STANDARD TEST COURSE AND APPROACH PROCEDURES

The vertical and horizontal course of flight to be followed during testing was expected to have considerable influence on FTE. Changes in workload associated with power and altitude requirements for turn anticipation, the length of course legs available to stabilize aircraft headings, and display characteristics all influence FTE and so are meaningful subjects of study in their own right. However, for the purposes of the present work, a standard set of procedures that were designed specifically for this study were flown.

- Approach Procedure

  The plan and profile views of the three approach procedures that were used in this study are illustrated in NOS format in Figures 6, 7, and 8. Mirror images of these procedures were also used and were designed to accommodate changes in the active runway due to wind direction. The procedure illustrated in Figure 6 includes a 120 degree turn from the initial to the intermediate approach segment and a 30 degree intercept to the final approach course. The minimum altitude is level from the IAF to the IF, descends at 150 feet per mile between the IAF and the FAF, and at 380 feet per mile from the FAF to the MAP. The procedure shown in Figure 7 differs from that in Figure 6 in that the initial and intermediate segments have been lengthened to 10 miles. In Figure 8 the IAF was moved to the 120 degree turn, the IF was at the 30 degree turn, and the intermediate segment was in line with the final approach to provide a straight entry to the final approach course. The descent rate between the IF and the FAF remains at 150 feet per mile.

  The missed approach in each procedure requires the pilot to fly runway heading for 5 nm and climb to 3000 feet, then make a 90 degree turn to the left and fly 5 nm to the waypoint defining the hold, while climbing to 4370 feet.

- CDI Sensitivity

  The approach sensitivities were as specified in TSO C129 with an automatic increase in sensitivity changing from 1 nm full scale to 0.3 nm full scale 2 miles before the FAF.

- Turn Anticipation

  The test pilots were instructed not to use the turn anticipation feature of the receiver and to base all turn initiation on their own judgment with reference to the distance-to-waypoint information that was continuously shown on the GPS receiver display.

- Airspeeds

  The pilots were be instructed to make each approach at the Category B airspeed that they would normally use.

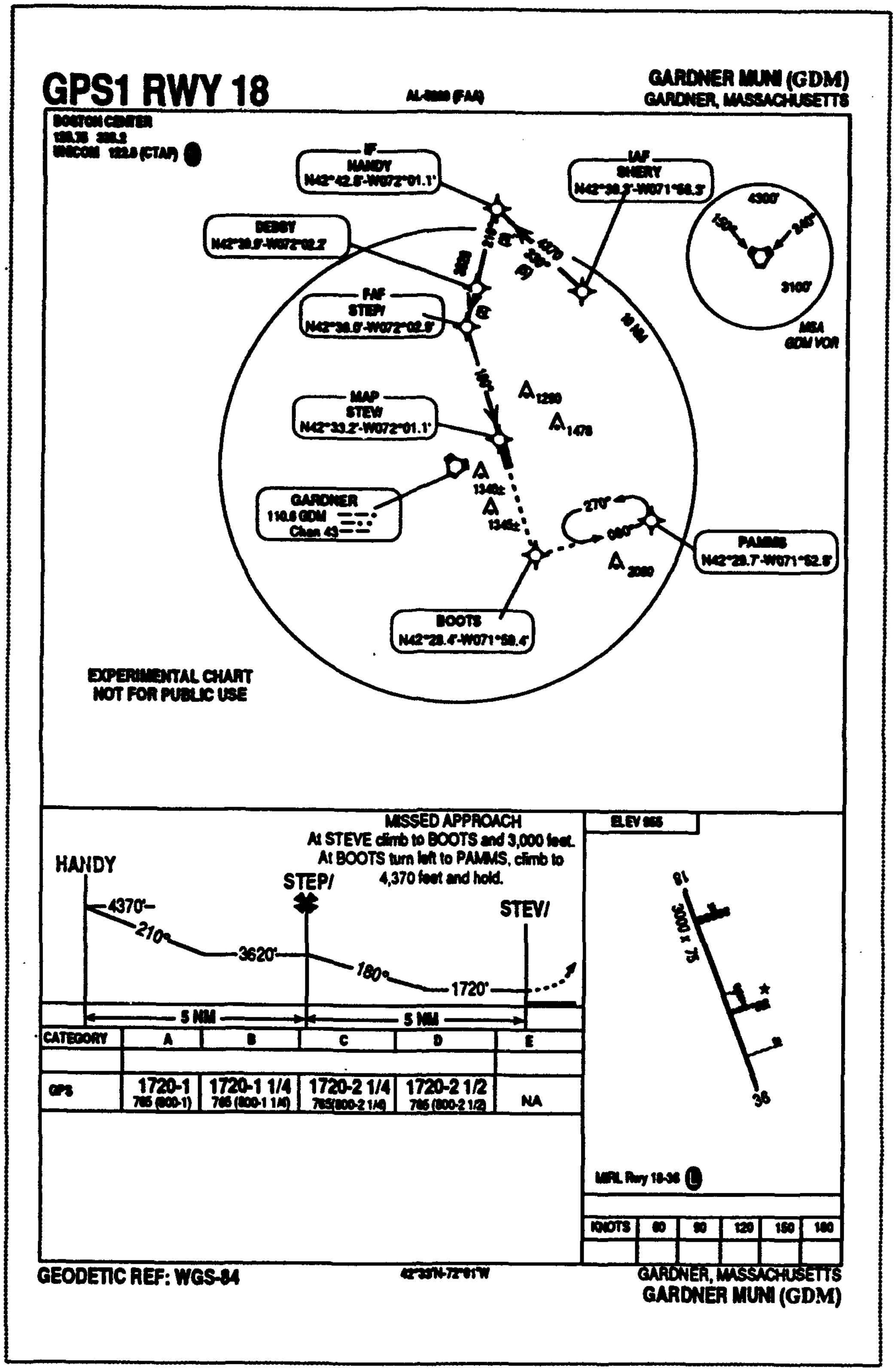

Figure 6. Instrumental procedures approach plate for approach with 30 degree turn at the FAF, following a 5 nm intermediate segment

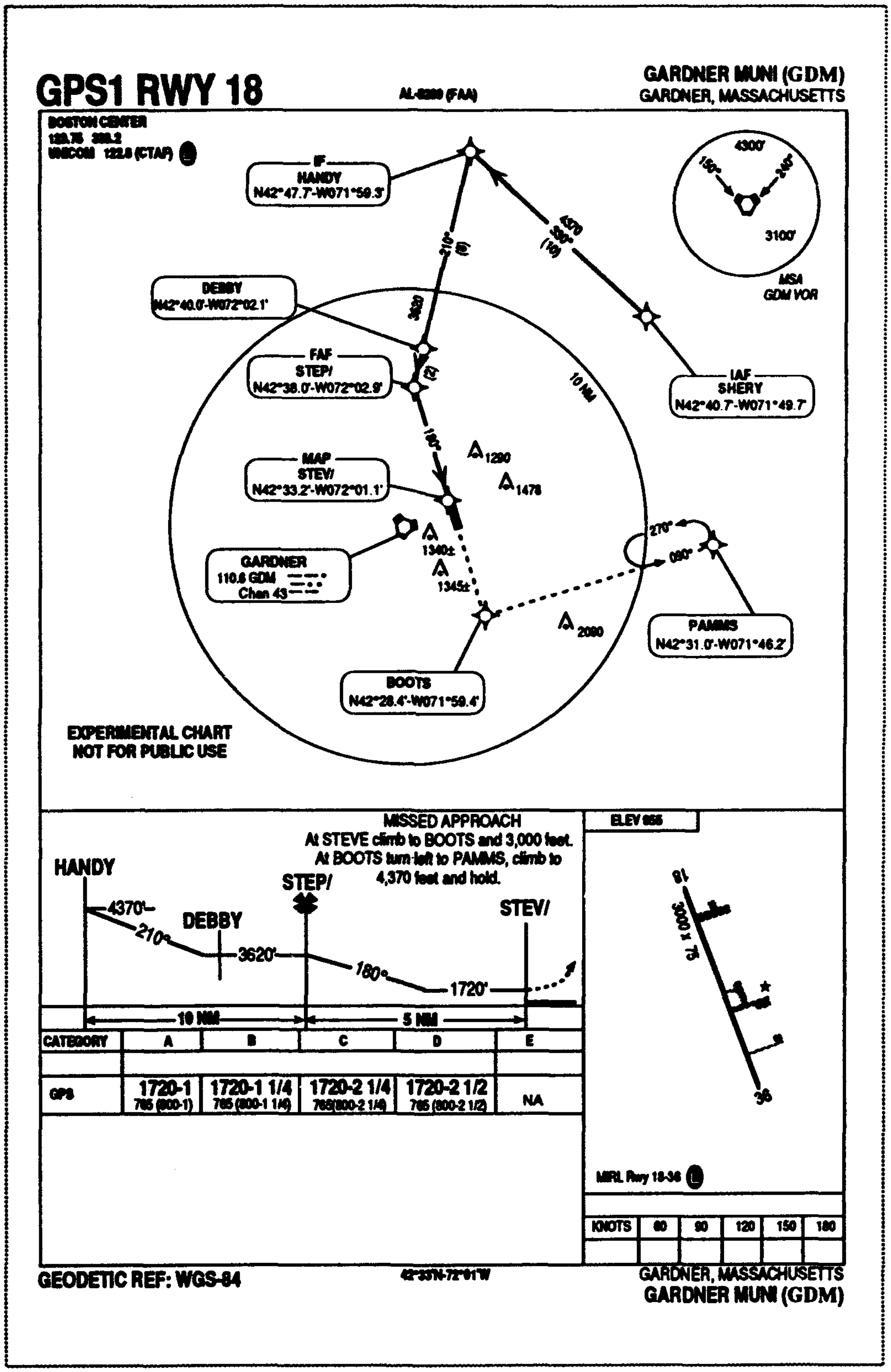

Figure 7. Instrument procedures approach plate for approach with 30 degree turn over the FAF, following a 10 nm intermediate segment

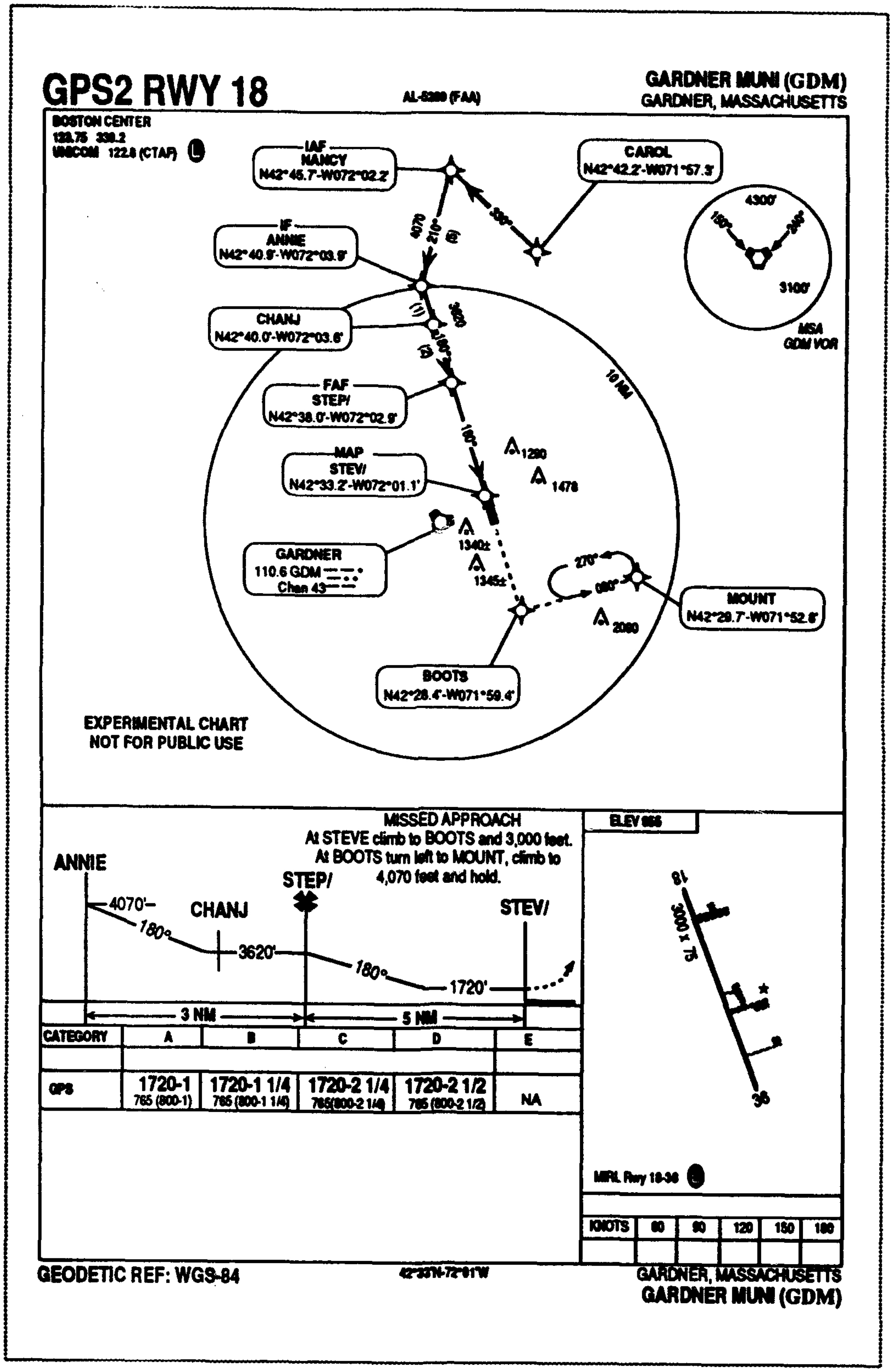

Figure 8. Instrument procedures approach plate for approach with 30 degree turn 3 nm before the FAF

3.7 CREW RESPONSIBILITIES

Data Collection Technician

The technician who ran the data collection equipment, using a Halikan PC, sat behind the safety pilot. On each flight the technician

- Initiated computer data collection procedures.
- Maintained data collection forms.
- Verified that the data collection apparatus was functioning during testing.
- Scanned outside for other traffic.
- Recorded wind and visibility conditions.
- Observed and recorded anomalous pilot and procedural conditions that may be useful in interpreting data collected during the approach.

Safety Pilot

The safety pilot flew the aircraft in and out of Minuteman Airfield at Stow which has a relatively short runway.

In addition to ensuring the safety of the flight, the safety pilot

- Screened potential test pilots.
- Conducted preflight and postflight briefing.
- Prepared and preflighted the aircraft.
- Scanned for other traffic.
- Communicated with ATC about matters peculiar to the research, and handled traffic-related calls when the test pilot was under the hood.
- Administered the workload scale to the pilot following completion of the fourth and eighth approach.
- Checked the receiver for HDOP prior to each approach.
- Estimated the runway wind conditions.

- Noted anomalous occurrences that might be important to understanding the data.

Test (subject) Pilot

The test pilot was responsible for all normal aircraft instrument flight operations and communications directly related to executing the approach procedures, including standard announcements on the CTAF. The test pilot

- Selected the appropriate experimental instrument approach chart upon direction by the safety pilot.

- Executed the test approaches and missed approach procedures, as the sole manipulator of the aircraft controls.

- Provided estimates of pilot workload.

3.8 TEST PROCEDURES

Order of Conditions

Each pilot flew one practice approach and a total of eight data collection trials in one day. Six of the pilots flew four approaches with the turn at the FAF first and then four more approaches with the turn before the FAF. The other six pilots flew the courses in the reverse order.

To avoid excessive fatigue, two to four test approaches were flown in the morning and four to six after a rest at noon.

Testing in the morning session included a briefing session, practice operating the GPS receiver, one practice approach, at least two data collection flights at Gardner, and a lunch break at a restaurant nearby. The remaining four to six approaches were flown in the afternoon without practice approaches. The test pilot flew the aircraft to and from Minuteman, but landings and takeoffs at Minuteman were made by the safety pilot.

All test procedures were reviewed and approved by an independent Institutional Review Board operated in accordance with the rules established by the U.S. Department of Health and Human Services.

Introduction and Briefing

The following sequence of events transpired for each test pilot during the morning of the test day:

- The pilot's license, medical certificate, and logbook were examined.

- The purpose of the experiment, procedures to be used, and nature of the cooperation required from the pilots were explained in detail.

- The test pilots were familiarized with the airplane and its instrumentation by sitting in the cockpit for a few minutes and examining the cockpit layout.

- The test pilots then returned to the briefing room and read a short description of the study that included a statement to the effect that they were free to stop their participation in the research at any time. They were then asked to sign a statement indicating that they understood what they were being asked to do and that they wanted to participate in the study.

- The pilots were then instructed in the use of the GPS and reviewed and practiced the control use sequences that were required with the receiver during the approaches.

- The pilots were given for review a chart of the local area and the approach plates that they were to use during practice and test flights. The pilots were instructed to study the approach plates carefully, particularly the headings required for the different segments of the procedures, and the descent rate that was required on the final approach to reach the MDA prior to the MAP.

- A review of the aircraft's operating procedures was conducted with the test pilot. These included take off and approach speeds, power settings, and engine out procedures. The approach charts for the practice and test runs were also reviewed along with suggested initial power settings for the approaches.

- The pilots were instructed on how to use the two workload scales.

Practice

Following the briefing, the three-person crew flew to Gardner field and the test pilot flew one of the two GPS-defined courses. After completing the missed approach, the safety pilot requested the test pilot to indicate the difficulty of the approach using the Volpe Center workload scale in order to ensure that the pilot knew how to use the scale in flight.

Data Collection Flights

The test pilots flew to the initial approach fix as directed by the safety pilot, and then flew two to four data runs during the remaining hours of the morning.

A one-hour break for lunch was taken. The test pilot then flew four to six more data runs in the afternoon. No specific guidance or hints on flight procedures were given to the test pilots beyond their initial training and practice trial. The test procedures were flown based on the information contained on the experimental approach procedure charts that were shown on the

GPS receiver display (name of upcoming waypoint and distance to that waypoint) and on the CDI.

Debriefing

Following each day's flight procedures, the pilots were asked the following:

- To state and discuss their reactions and preferences regarding the change in CDI sensitivity prior to the FAF.
- To compare the difficulty of GPS procedures with other instrument procedures that they are familiar with, such as VOR or NDB approaches.
- To discuss their concerns about full-scale deflections of the needle in turns and the strategy that they used to negotiate turns through dead reckoning.

4. DATA ANALYSIS AND INTERPRETATION

The four objectives of this study were the following:

- To determine if the CDI sensitivities specified in TSO C129 for non-precision approaches are "flyable" by low time general aviation pilots.

- To determine if TERPS currently used for VOR, VOR DME, and NDB approaches were sufficiently conservative to be used for non-precision approaches made using non-differential GPS for guidance.

- To measure the flight technical error generated by general aviation pilots using positive course guidance for missed approaches.

- To determine the comparability of FTE data collected in Category A approaches flown with Loran with that collected during the Category B approaches of this study.

CRITERIA OF SUCCESS

CDI Sensitivities

The sensitivities will be considered acceptable if the following conditions are met:

- The CDI deflection is less than full scale during the last four miles of the approach.

- The pilots felt that flying the TSO sensitivities was not so demanding that they had insufficient spare time to attend to additional tasks, if so required.

VOR Overlay

Non-differential GPS will be considered suitable for current NDB and VOR approaches if it can be shown that system error associated with flying these approaches with GPS falls within the boundaries of the intermediate and final approach trapezoids designed for off-site VOR instrument approaches. These trapezoids are the smallest of those used to define terminal procedures for non-precision approaches. For purposes of this study, total system error comprises flight technical error and the error in the position solution of the GPS receiver. Flight technical error at any point in time is indicated by the displacement of the CDI from center. Position solution error will be considered to be 100 meters. This is the size of the worst case error produced by DOD's use of the selective availability factor to degrade GPS satellite position information. DOD guarantees that the SA-associated error will be no greater than 100 meters 95 percent of the time.

The trapezoids are illustrated in Figure 9. To satisfy the criteria indicated by this figure, total system error must have no more than a 5 percent probability of exceeding the boundaries of these two trapezoids. This includes a 95 percent probability of passing the intermediate fix (IF) within two miles when that fix is the apex of a 120 degree turn; passing the final approach fix within 1 nm when its intersecting segments form a 30 degree angle; and passing the missed approach point located on the extended centerline of the runway within 1.25 nm of this centerline.

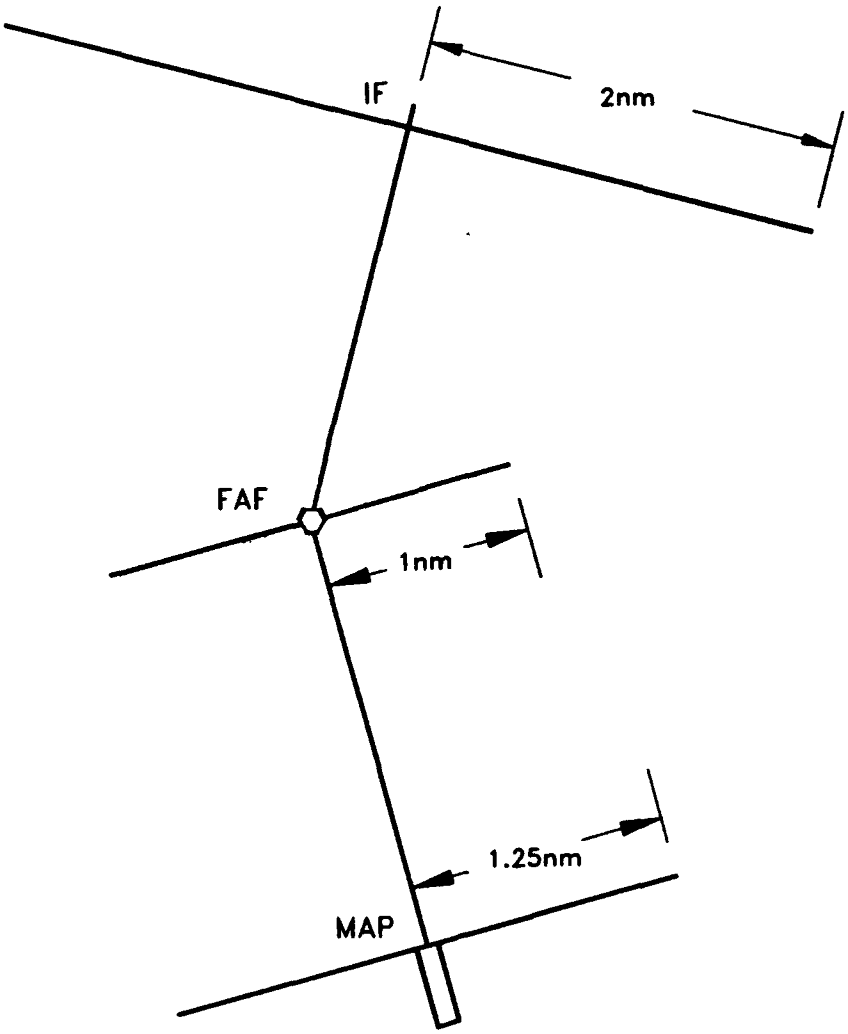

Figure 9. Dimensions of TERPS for off-site VOR

Comparability with Category A

Data collected during this study will be considered comparable to those collected earlier in the Category A study if the following criteria are met:

- The pilot can fly with an acceptable level of workload and CDI sensitivity at 0.30 nm, full scale.
- The final approach course is flown with approximately the same level of accuracy, i.e., an RMSE for FTE of approximately 0.09 nm. at the FAF and .05 nm at the missed approach point.

DATA

Flight Technical Error

Flight technical error was measured once per second from the start of the 120 degree turn through the completion of the missed approach. The flight technical error data for the analysis of performance through the whole procedure was distributed into a number of one- or two-mile sections. These divisions separate the straight sections from the sections where pilots were dead reckoning through the curves. Figures 10 and 11 represent the two basic courses flown and show how the data were grouped.

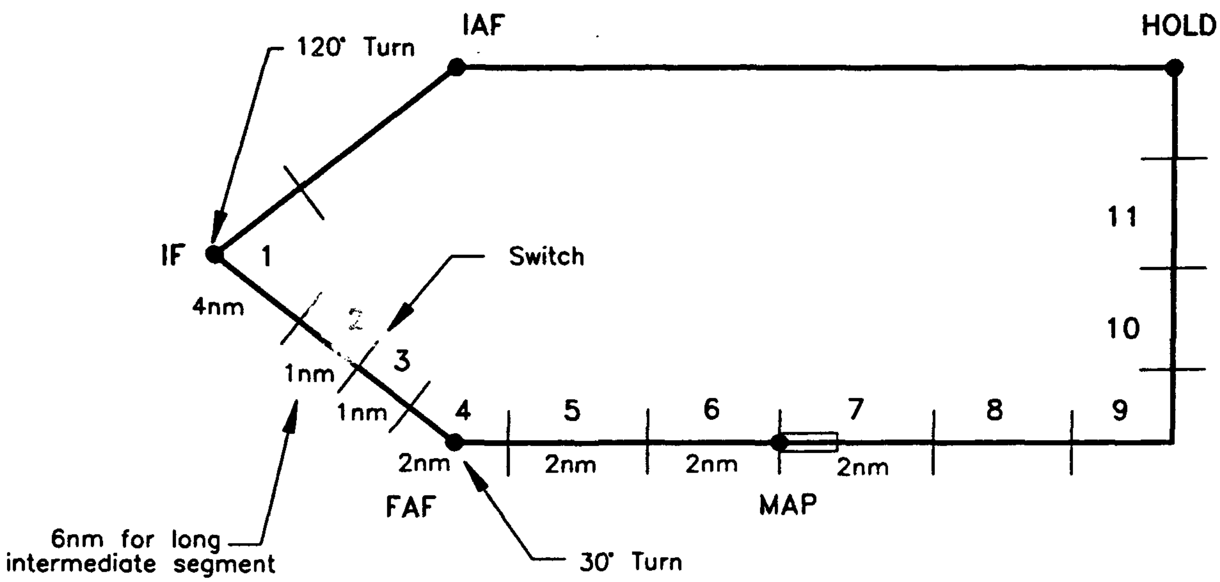

Figure 10. Plan view of course with 30 degree turn at FAF showing sections used for grouping data

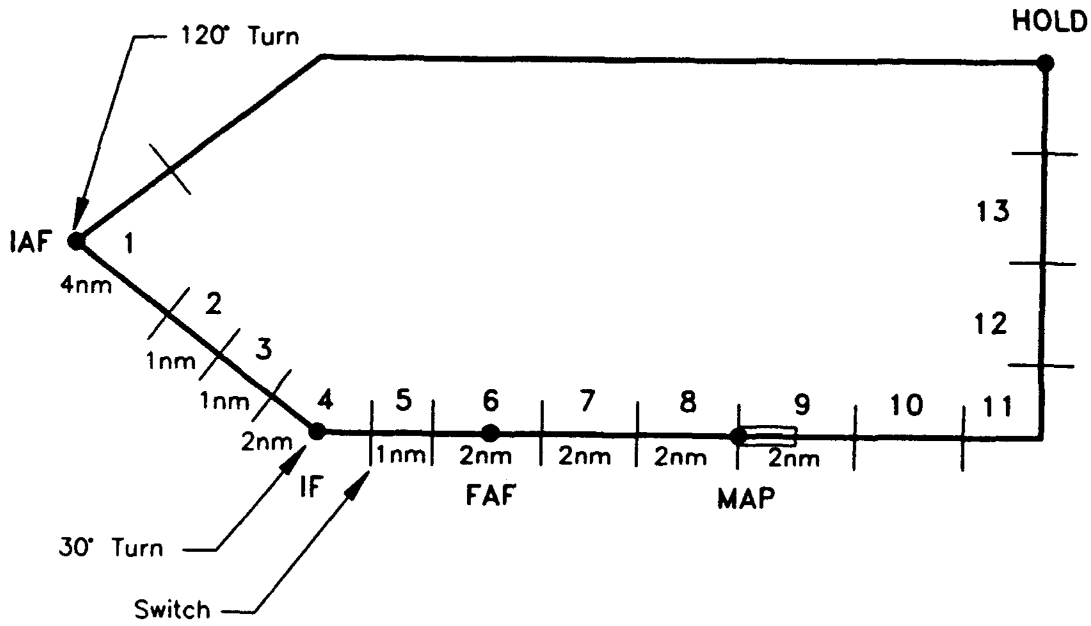

Figure 11. Plan view of course with 30 degree turn 3 nm before the FAF showing sections used for grouping data

- <u>Turns from Initial and Intermediate Segments</u>

Table 1, 2 and 3 show FTE data of the 12 pilots grouped according to the sections shown in Figures 10 and 11. The data in Table 1 are from the first five pilots who turned at the FAF following a five-mile segment between the IAF and the FAF. After data from the first five pilots were collected, the intermediate segment was lengthened to 10 miles. The data from the remaining seven pilots are shown in Table 2.

Table 1. FTE in nautical miles for five pilots flying approaches with 5 nm intermediate segment and 30 degree turn at the FAF

	Section	-2.74 Std Dev*	Mean	+2.74 Std Dev*	CDI Sens
120° →	1	-0.91	0.02	0.94	1.0 nm
	2	-0.77	-0.03	0.71	
Switch →					
	3	-0.60	0.03	0.65	0.3 nm
30° FAF →	4	-0.51	-0.01	0.49	
	5	-0.46	0.03	0.53	
	6	-0.24	0.02	0.29	
MAP →					
	7	-0.37	0.06	0.49	

* Based on 95% upper confidence level for sigma using 1.37 times σ as the adjustment factor for the small sample size.

Each table includes three columns of data. The center column indicates average FTE, the columns on either side of it show the FTE values expected to be reached or exceeded 5 percent of the time during the universe of approaches from which our sample of approaches was taken. The constant used to generate the values in Table 1 is larger than that in Tables 2 and 3 because it is based on data from fewer approaches. Hence, the numbers in these outside columns are influenced by both pilot performance and the small sample sizes.

Table 2. FTE in nautical miles for seven pilots flying approaches with 10 nm intermediate segment and 30 degree turn at the FAF

	Section	-2.58 Std Dev*	Mean	+2.58 Std Dev*	CDI Sens
120° →	1	-1.06	-0.07	0.92	1.0 nm
	2	-0.51	0.00	0.51	
Switch →					
	3	-0.28	0.00	0.28	0.3 nm
30° FAF →	4	-0.34	-0.05	0.24	
	5	-0.20	-0.01	0.19	
MAP →	6	-0.11	0.00	0.11	
	7	-0.22	0.04	0.31	

* Based on 95% upper confidence level for sigma using 1.29 times σ as the adjustment factor for the small sample size.

The boxed sections in the tables contain data collected while the pilot was flying straight sections of the procedure with positive course guidance. The sections not boxed represent sections of the approach where the pilot was likely to be dead reckoning through the turns. Sections 1 through 2 were flown at a sensitivity of 1 mile full-scale. Sections 3 through 6 were flown at a sensitivity of 0.3 nm. The sensitivity switched back to 1 mile full-scale at the MAP.

Notice that in all 3 tables the CDI was well within full scale (FTE less than 1.0 nm.) when the sensitivity was at 1.0 and the pilots were flying the straight segments of the procedures.

After the switchover, a value of 0.30 or greater indicates a full scale deflection. Tables 1 and 3 indicate a probability of greater than .05 of a full scale deflection following the switchover. In Table 2, the probability of a deflection of this size is less than 0.05. The apparent reason for this difference is the distance at which the switchover point follows a turn. Table 1 and 2 indicate the results of a procedure where a switchover is 3 nm or less following a turn. Table 2 represents a procedure where the switchover is 8 miles past the apex of a 120 degree turn.

Table 3 shows the data collected from the 12 pilots when they made a straight approach to the FAF as depicted in Figures 8 and 11.

Table 3. FTE in nautical miles for twelve pilots flying approaches with 30 degree turn prior to the FAF

		Section	-2.42 Std Dev*	Mean	+2.42 Std Dev*	CDI Sens
120°	→	1	-0.88	-0.05	0.79	
		2	-0.67	0.02	0.71	1.0 nm
		3	-0.93	-0.04	0.85	
30°	→	4	-0.86	-0.06	0.74	
Switch	→					
		5	-0.69	-0.03	0.63	
FAF	→	6	-0.27	0.00	0.28	0.3 nm
		7	-0.18	-0.02	0.15	
MAP	→	8	-0.13	0.00	0.14	
		9	-0.19	0.05	0.29	

* Based on 95% upper confidence level for sigma using 1.21 times σ as the adjustment factor for the small sample size.

Final Approach

For the objectives of this study the most critical element of pilot performance is the final approach. Performance on final is represented in Sections 4, 5, and 6 in Tables 1 and 2, and Sections 6, 7, and 8 in Table 3. Table 3 shows that when the 30 degree turn was made 2 miles before the FAF, the probability of a full-scale deflection on final is less than 0.05 in each of the 3 segments. Tables 1 and 2 show that when the turn was made at the FAF, the probability of a full-scale deflection was greater than 0.05 in two of the final approach sections when a 5 nm intermediate segment followed the 120 degree turn, but only in the section at the FAF when a 10 nm intermediate segment is used. In fact, when a 10 mile intermediate segment was used before a 30 degree turn at the FAF, FTE performance was comparable to that produced when the FAF follows a 3 nm segment aligned with the final approach course.

In order to examine the reliability of the apparent influences of these differences in approach procedure on performance of the final approach, FTE scores were transformed to RMS error scores (Table 4) and the statistical significance of the differences among these scores was tested.

Table 4 shows the average RMS error of the FTE performance in the three sections of the final approach course for the three procedures represented in Tables 1, 2, and 3. The N column indicates the number of approaches that were used to generate the RMS error scores. An analysis of variance using the General Linear Model Procedure in SPSS was used to compare the RMS error values among the cells. For the purposes of this analysis, the data in the right-hand column were combined because they are nearly identical and they represent performance on the same approach procedure.

Table 4. Mean RMS flight technical error in nautical miles on final approach following 30 degree turns at and before the FAF

	At the FAF			Before the FAF		
	Section	RMSE	N	Section	RMSE	N
5 nm segment (5 pilots)	4	.16	19*	6	.10	18*
	5	.13	19	7	.05	18
	6	.07	19	8	.05	18
	$\bar{x}$ =	.12		$\bar{x}$ =	.07	
10 nm segment (7 pilots)	4	.11	28	6	.09	28
	5	.06	28	7	.06	28
	6	.04	28	8	.05	28
	$\bar{x}$ =	.07		$\bar{x}$ =	.07	

* Data from 3 approaches lost due to equipment malfunctions

Significant differences for the following conditions were found:

(1) Approach procedure. ($F= 8.34$; $df= 2,263$: $p< 0.0003$)
(2) Section on final.($F= 19.02$; $p< 0.0001$)
(3) Pilots. ($F= 3.19$; $df= 11$, $p<0.0004$)

A Tukey-Kramer Honest Significant Differences technique used to control for multiple comparisons was applied to the data in the three approach procedure conditions, and in three sections on the final approach to identify differences within these conditions that were statistically significant.

Using an α of 0.05 the following relations among the procedures are statistically significant:

(1) With turns at the FAF, FTE was less following a 10 mile intermediate segment than it was following a 5 mile segment.

(2) With a 5 mile segment, FTE was greater with turns at the FAF than when the turns were made 2 miles before the FAF.

Differences in performance on approaches made following turns at the FAF after a 10 mile intermediate segment and those following turns made 3 miles before the FAF were not statistically significant.

These results indicate that 10 nm intermediate segments can be used to compensate for the destabilizing effect of 30 degree turns over the FAF following a 120 degree turn. They verify the current TERPS requirement for 10 nm intermediate segments following 120 degree turns. Using an α of 0.05, the statistical significance of the differences among the three sections on final approach are as follows:

(1) Performance in the section at the FAF is worse than that in either of the two subsequent sections.

(2) Differences between performance in the second section and the final section at the MAP are not statistically significant.

When a constant sensitivity CDI is used, FTE performance improves inside the FAF but does not continue to improve throughout the approach. It is possible that an angular sensitivity profile would produce FTE performance that improves right down to the MAP, even during non-precision approaches. The possibility of such an effect should be investigated.

Visual inspection of the ground tracks of different pilots showed obvious differences in capability among the pilots of our sample. We did not test these differences for statistical significance.

Replication of Category A Results

Performance on final approach was comparable to that obtained in an earlier study using a Category A single engine aircraft. Table 5 shows RMSE in each of the three windows as a function of CDI sensitivity for a Category A approach. In this study, 12 general aviation pilots flew a Piper Archer through an approach course defined by Loran waypoints. The complete course was flown with the indicated CDI sensitivity. The course included a 60 degree turn at the IAF, a 5 mile intermediate segment, a 30 degree turn at the FAF, and a 5 nm final approach. There was no sensitivity switch or other disruption during the intermediate segment so it was somewhat easier to fly than the two in the present study that required a turn at the FAF. The approach with the 10 mile intermediate segment is probably the one most comparable to that used in the Category A study. Performance during the turn at the FAF was slightly better on the Category A approaches, but in general, performance

between the two categories was similar and increases our confidence in the advantages of the 0.30 nm CDI sensitivity for non-precision approaches.

Table 5. RMS flight technical error in nautical miles for twelve pilots on final approach with 6 levels of CDI sensitivity

	Final Approach Section	CDI Sensitivity (nm, full scale) 2.50	1.25	0.62	0.31	0.16	0.08	$\bar{x}$
FAF →								
	I	0.26	0.15	0.14	0.09	0.06	0.06	0.13
	II	0.23	0.11	0.08	0.05	0.03	0.03	0.09
	III	0.14	0.08	0.08	0.05	0.05	0.03	0.08
MAP →								
	$\bar{x}$	0.21	0.11	0.10	0.07	0.05	0.04	0.10

Further Examination of Performance on Final Approach

In order to obtain a finer-grained view of FTE performance on final approach, we selected for study the CDI displacement position recorded only at the 10 half-mile locations between the FAF and the MAP for each approach.

The mean and 95 percent probability values of these displacements are shown in Table 6 and 7. These tables show FTE data of the 12 pilots grouped according to the approach procedures that they flew. In the left half of each table is shown the data collected when the pilots were required to make a 30 degree turn at the FAF; the right half of each table shows the data collected from approaches where the pilots made a straight approach to the FAF. The data in Table 6 are from the first 5 pilots who turned at the FAF following a 5 mile segment between the IAF and the FAF. The data from the remaining 7 pilots, who flew a 10 mile intermediate segment are shown in Table 7. Each group of pilots flew the same approach procedure when the turn was made before the FAF.

Table 6. FTE in nautical miles at 10 points along a 5 nm final approach for five pilots following 30 degree turns at the FAF and 3 nm before the FAF. Length of the intermediate segment before the turn at the FAF was 5 nm.

	At the FAF			Before the FAF		
NM to MAP	-2.84 Std Dev*	Mean	+2.84 Std Dev	-2.84 Std Dev	Mean	+2.84 Std Dev*
4.5	-0.69	-0.08	0.51	-0.20	0.03	0.26
4.0	-0.46	0.05	0.56	-0.27	-0.01	0.25
3.5	-0.49	0.08	0.65	-0.28	-0.02	0.24
3.0	-0.53	0.07	0.67	-0.18	-0.01	0.16
2.5	-0.58	0.04	0.66	-0.20	-0.03	0.14
2.0	-0.43	0.00	0.43	-0.19	-0.02	0.15
1.5	-0.34	0.00	0.34	-0.17	0.00	0.17
1.0	-0.34	0.03	0.40	-0.12	0.02	0.16
0.5	-0.25	0.03	0.31	-0.12	0.02	0.16
0.0	-0.17	0.03	0.23	-0.14	0.03	0.20

* Based on a 95% upper confidence level for sigma using 1.42 times σ as the adjustment factor for the sample size

Table 7. FTE in nautical miles at 10 points along a 5 nm final approach for seven pilots following 30 degree turns at the FAF and 3 nm before the FAF. Length of the intermediate segment before the turn at the FAF was 10 nm.

	At the FAF			Before the FAF		
NM to MAP	-2.65 Std Dev*	Mean	+2.65 Std Dev	-2.65 Std Dev	Mean	+2.65 Std Dev*
4.5	-0.45	-0.13	0.19	-0.25	-0.01	0.23
4.0	-0.35	-0.03	0.29	-0.18	0.01	0.20
3.5	-0.29	-0.02	0.25	-0.17	-0.01	0.15
3.0	-0.23	-0.02	0.19	-0.23	-0.02	0.19
2.5	-0.21	0.00	0.21	-0.22	-0.01	0.20
2.0	-0.18	0.01	0.20	-0.18	-0.02	0.14
1.5	-0.13	0.00	0.13	-0.19	-0.03	0.13
1.0	-0.11	0.00	0.11	-0.14	-0.01	0.12
0.5	-0.13	0.00	0.13	-0.20	-0.01	0.18
0.0	-0.13	0.00	0.13	-0.16	0.00	0.16

* Based on a 95% upper confidence level for sigma using 1.375 times σ as the adjustment factor for the sample size

Each table includes six columns of data, three for each approach procedure. For each approach, the center column indicates average FTE, the columns on either side of it show the FTE value expected to be reached or exceeded 5 percent of the time during the universe of approaches from which our sample of approaches was taken. The constant used to generate the values in Table 6 is larger than the constant in Table 7 because it is based on data from fewer approaches. The numbers in these outside columns are therefore influenced by both pilot performance and the number of approaches flown. These considerations aside, recall that the ANOVA reported above showed that the differences in performance on final approach with a turn at the FAF following 5 and 10 mile intermediate segments were statistically significant.

The data in the two tables are based on single sample of FTE taken on each approach at each of the 10 half mile points along the approach course. When the values in the outside columns are examined the following can be seen:

(1) Following a 30 degree turn over the FAF, there will be at least a 5 percent chance that the CDI will reach full-scale deflection (0.30 nm) at any point throughout the first 4 miles of the approach. This shows that it may take 4.5 miles to get reliably established on final approach after a 30 degree turn following a 5 mile intermediate segment, and indicates the difficulty of this procedure.

(2) When the turn follows a 10 mile segment (Table 7) the probability of a full scale deflection exceeds 0.05 during the first mile of the approach, but it is considerably less than that during the remaining 4 miles.

(3) Tables 6 and 7 both show that when the pilot has a 3 mile intermediate segment in line with the final approach course, the probability of a full scale deflection is less than 0.05 throughout the whole final approach.

Missed Approach Procedure

Table 8 shows that performance during the missed approach was considerably worse than performance on the approach. FTE increases following initiation of the "miss," are worst at the 90 degree turn, and then improve as the pilot proceeds to the hold waypoint. There are two likely reasons for this. First, the CDI sensitivity switched to 1.0 nm at the missed approach point, so the pilot could relax heading control and still keep the needle alive. Secondly, interviews with the pilots indicate that, even though positive course guidance was available throughout the procedure, the pilot usually went to dead reckoning as the climb was initiated and the gear and flaps were raised. The large deviations from the desired course result from lack of attention to the CDI during this cleanup period.

These data indicate that CDI sensitivity should be less than 0.30 nm for the miss and perhaps less than 1.0 nm if a 90 degree turn is to be incorporated in that procedure.

Table 8. FTE in nautical miles for twelve pilots flying the missed approach procedure

	Section	-2.78 Std Dev*	Mean	+2.78 Std Dev*
	7 **	-0.29	0.06	0.41
	8	-0.53	0.05	0.63
90° →	9	-1.64	0.02	1.68
	10	-1.27	0.37	2.02
	11	-0.96	0.09	1.13

* Based on 95% upper confidence level for sigma using 1.39 times σ as the adjustment factor for the small sample size.

** Data from approaches represented in Figures 9 and 10 were combined for analysis

Dead Reckoning Through the Turns

Pilots were instructed to fly through the turns without reference to the CDI for course guidance. The GPS display provided pilots with the distance to the apex of the turn but with no other turn initiation cues.

120 Degree Turn

Six of the 12 pilots said that they lead the turn by 1.5 nm. Lead distances ranged from 1 to 2 nm. Ground speed in the turn averaged 125 kts, with a range of 92 to 151 kts.

Figure 12 shows all 93 tracks through the turn. Points at 1/2-mile intervals were manually plotted for each track. The position of each data point was determined from the distance and bearing information provided by the GPS receiver relative to the active waypoint. The heavy solid lines drawn parallel with the course centerline indicate a full-scale deflection of the CDI at the terminal area sensitivity of 1.0 nm. This 2 mile corridor contains all but a 1/4-mile segment of one of the tracks. The pattern of tracks indicates that whereas most pilots turned well before reaching the apex waypoint, a number of them flew right by it. These overshooting tracks establish a bulge on the overshoot side of the curve, but remain within the 1-mile border. All tracks converge towards the centerline after completing the turn, but even three miles beyond the waypoint many tracks are further than 0.3 nm off the centerline. This indicates that when the CDI sensitivity switched, the needle went full scale for these pilots.

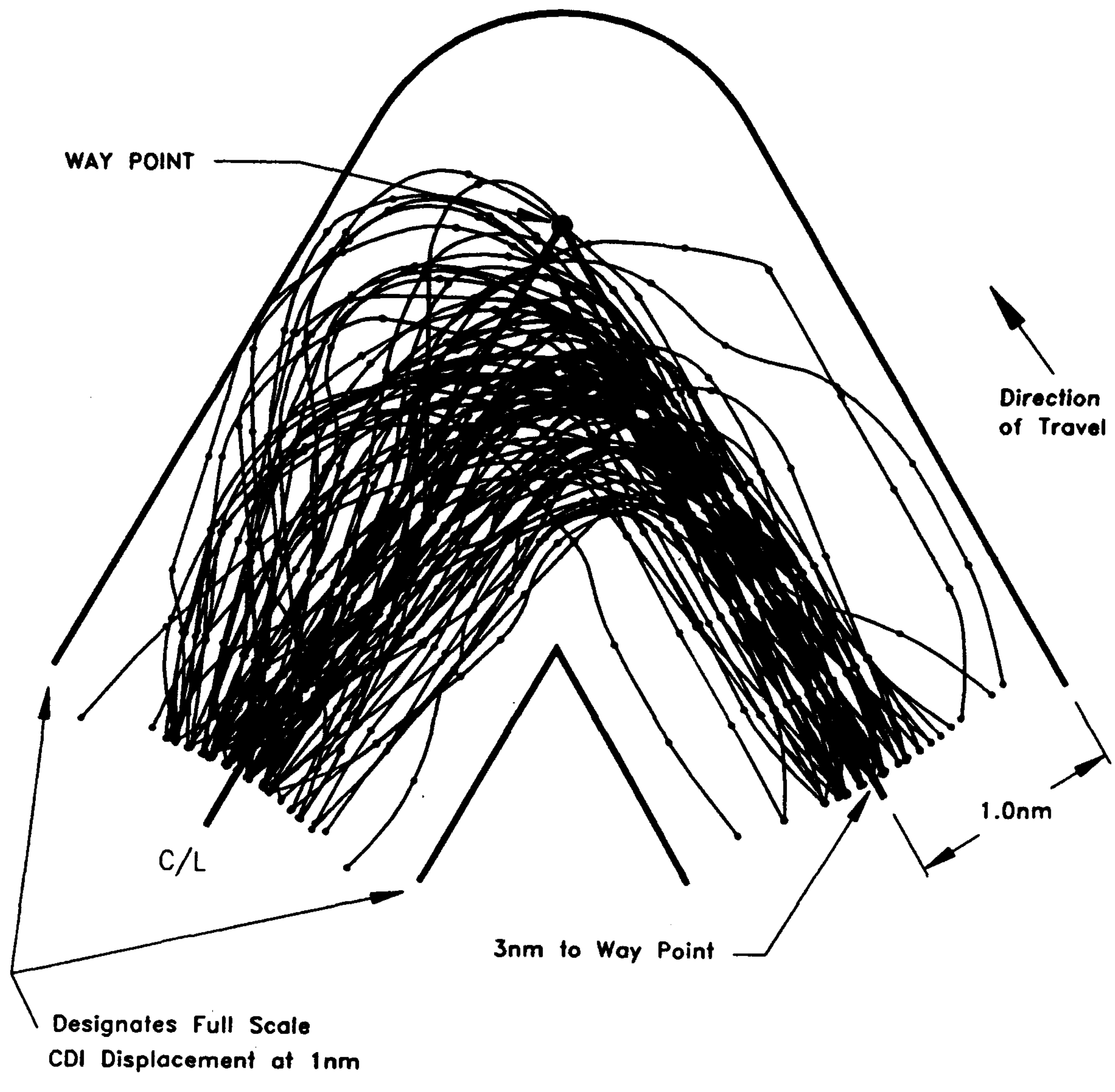

Figure 12. Ninety-three ground tracks made by twelve pilots flying through the 120 degree turn

30 Degree Turn at the FAF

Most pilots lead the 30 degree turn by 1 nm. Lead distances ranged from 0.2 to 1.5 nm. The average ground speed through the turn was approximately 110kts, with a range of 94 to 138 kts. Figures 13 and 14 show the track through the 30 degree turns for courses with the 5 mile intermediate segment and the 10 mile intermediate segment respectively. The figures show the ground tracks two miles on each side of the waypoint. The heavy line on either side of the centerline indicates the track displacement for which the CDI would be at full scale when set at 0.3 nm sensitivity. The pattern of tracks clearly show the influence of the 10 mile intermediate segment on FTE. The tracks shown in Figure 14 are less erratic and more completely contained within the 0.6 nm column defined by the CDI scale limits. There were no overshoots when the ten mile segment was used. However, two of the approaches did go outside the column on the inside of the curve.

30 Degree Turn before the FAF

Figure 15 shows the tracks made by the 12 pilots on the runs where they made the 30 degree turn prior to the FAF. The dark borders show the transition from 1 nm to 0.3 nm full-scale deflection that took place at the change waypoint. It is clear from these borders that the CDI went full scale on 12 of the 46 runs when the sensitivity switch occurred; 7 of these 12 were within the full-scale limits by the time the aircraft was within 1 nm of the FAF.

It is possible that the number of full-scale deflections could be reduced if the change to 0.3 nm sensitivity happened more gradually. A rampdown could be started four miles prior to the FAF with the sensitivity change being completed two miles before the FAF. The influence of such a rampdown procedure should be determined through flight testing.

90 Degree Turn during the Missed Approach

The requirement to arrest the climb at 3000 ft and maintain that altitude while reducing power and performing the 90 degree turn probably contributed to the high FTE demonstrated by the pilots through the turn.

Figure 16 is a hand plot of the aircraft ground track as indicated by the distance and bearing of the aircraft with regard to the active waypoint. All but two of the tracks indicate that the needle was at less than full scale (deviations were less than one mile from centerline) until the waypoint was reached. Most of the pilots did not turn early enough to avoid going beyond the waypoint, and a number of tracks went more than a mile beyond the course centerline. Some of these overshoots were the result of the pilot's turn strategy.

Two strategies are represented by the tracks illustrated in Figures 17 and 18. Figure 17 shows the tracks of a pilot who consistently failed to anticipate the turn. These overshoots may have occurred because the pilot was busy attending to the altitude requirements of the

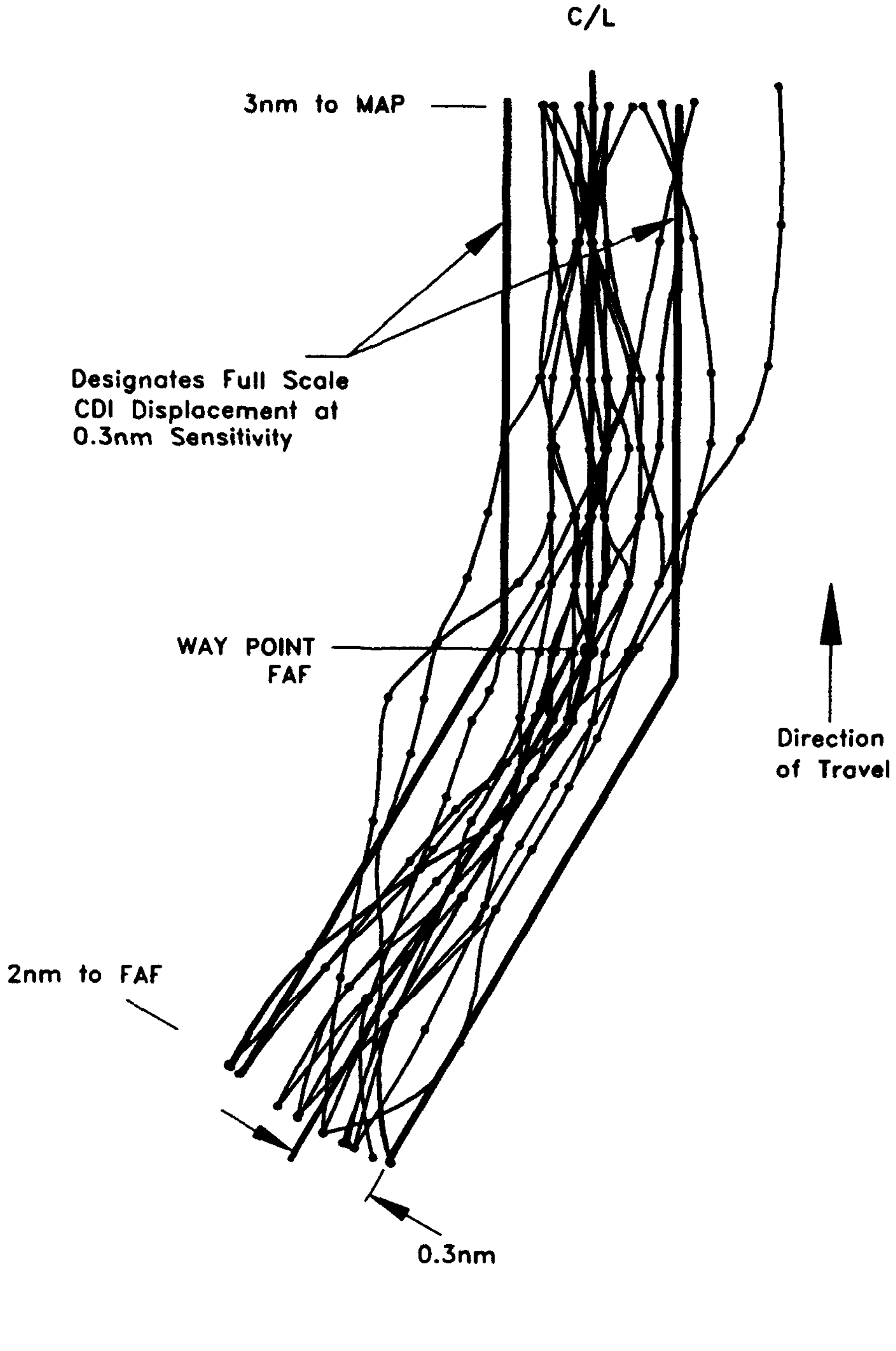

Figure 13. Nineteen ground tracks made by five pilots flying through the 30 degree turn at the FAF following a 5 nm intermediate segment.

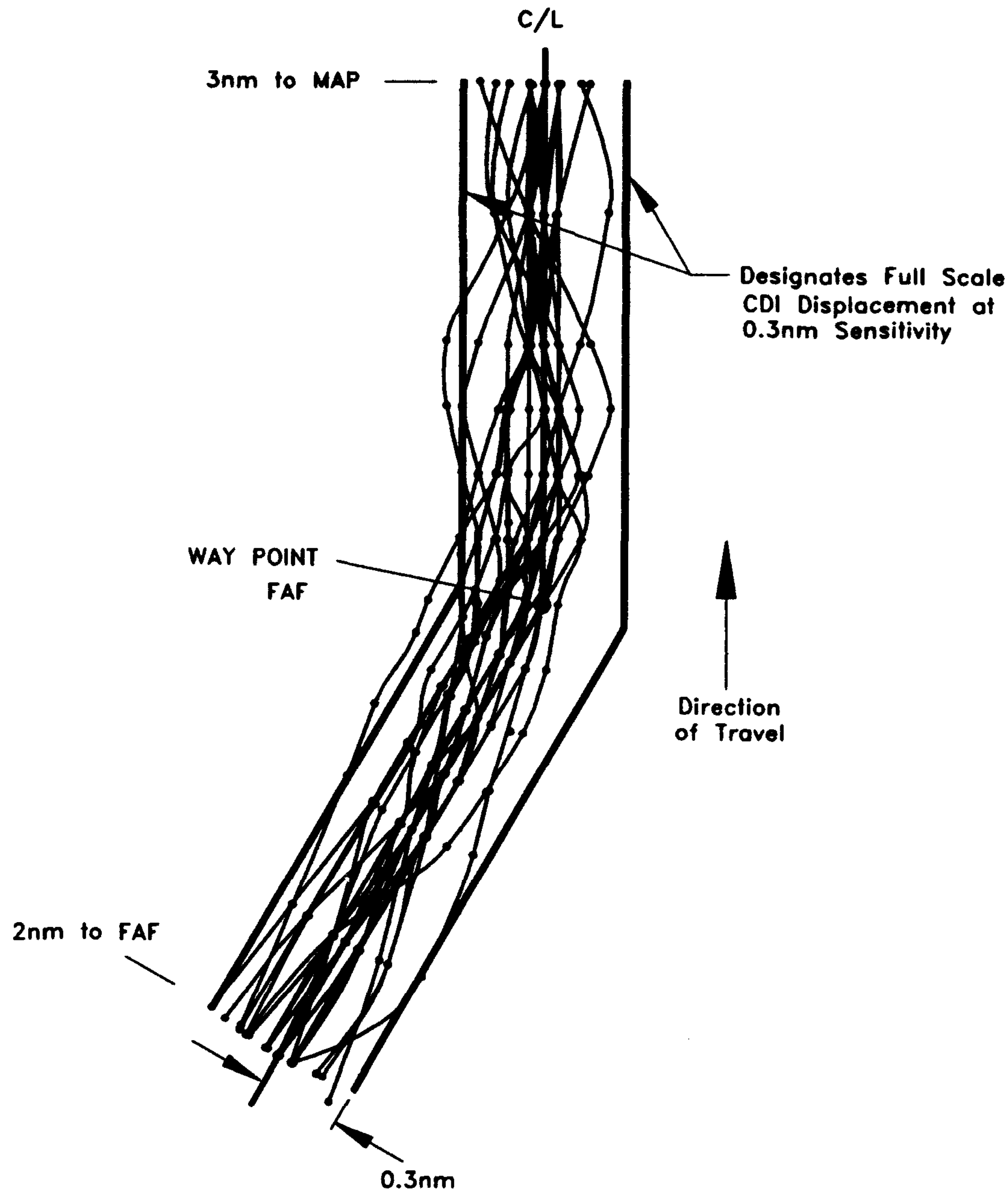

Figure 14. Twenty-eight ground tracks made by seven pilots flying through the 30 degree turn at the FAF following a 10 nm intermediate segment

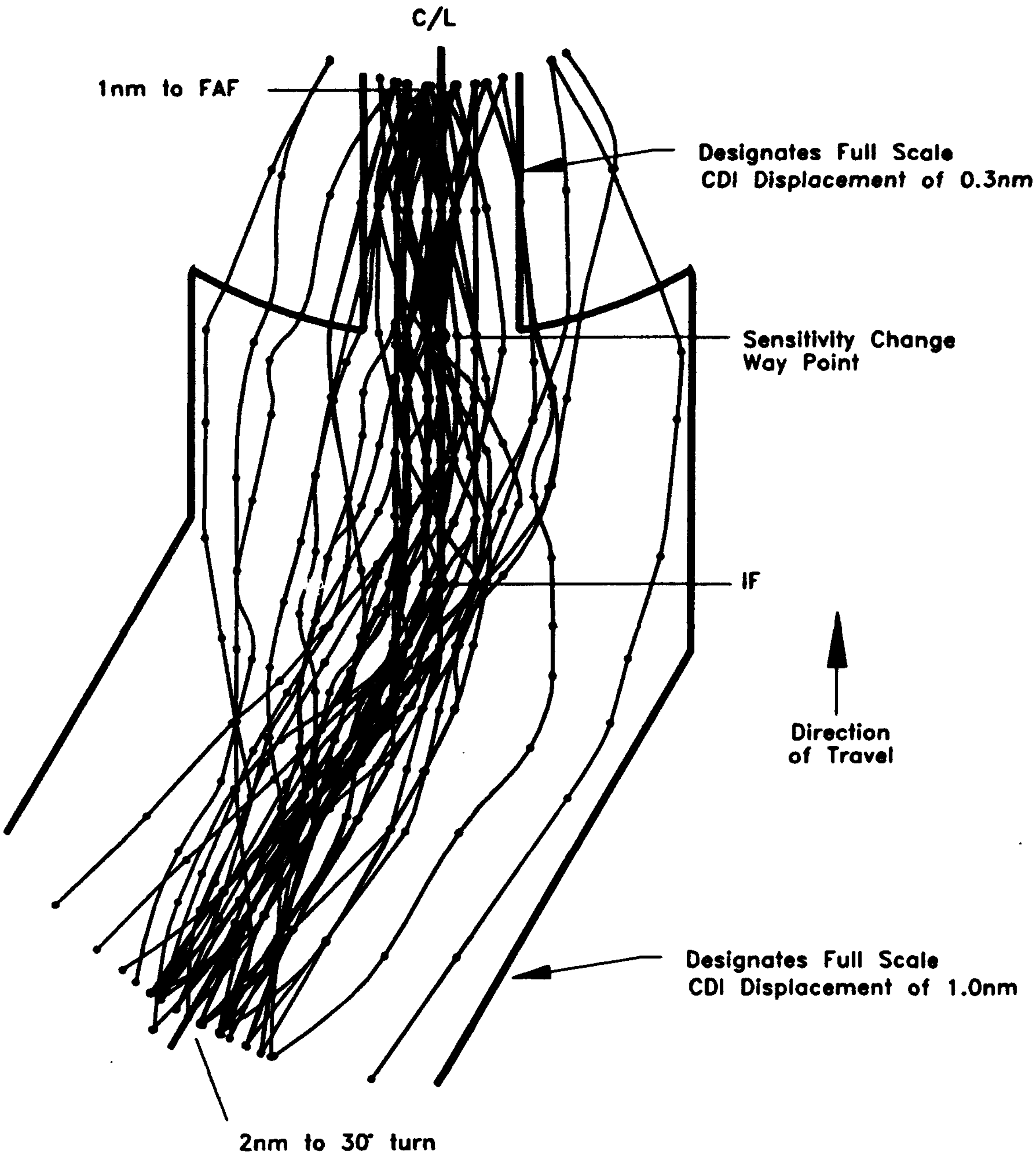

Figure 15. Forty-six ground tracks made by twelve pilots flying through a 30 degree turn 3 nm before the FAF

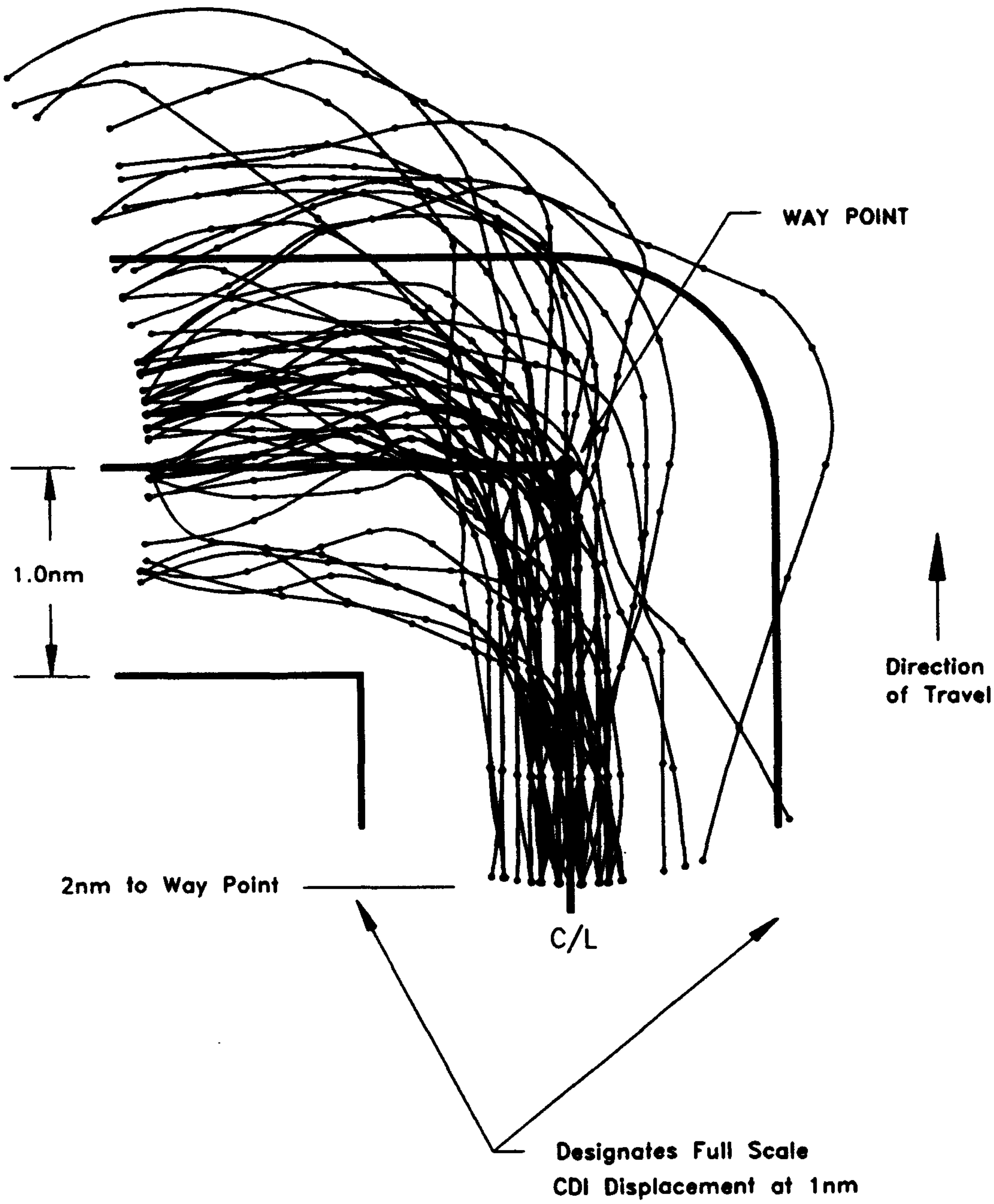

Figure 16. Sixty ground tracks made by twelve pilots flying through the 90 degree turn during missed approach procedure

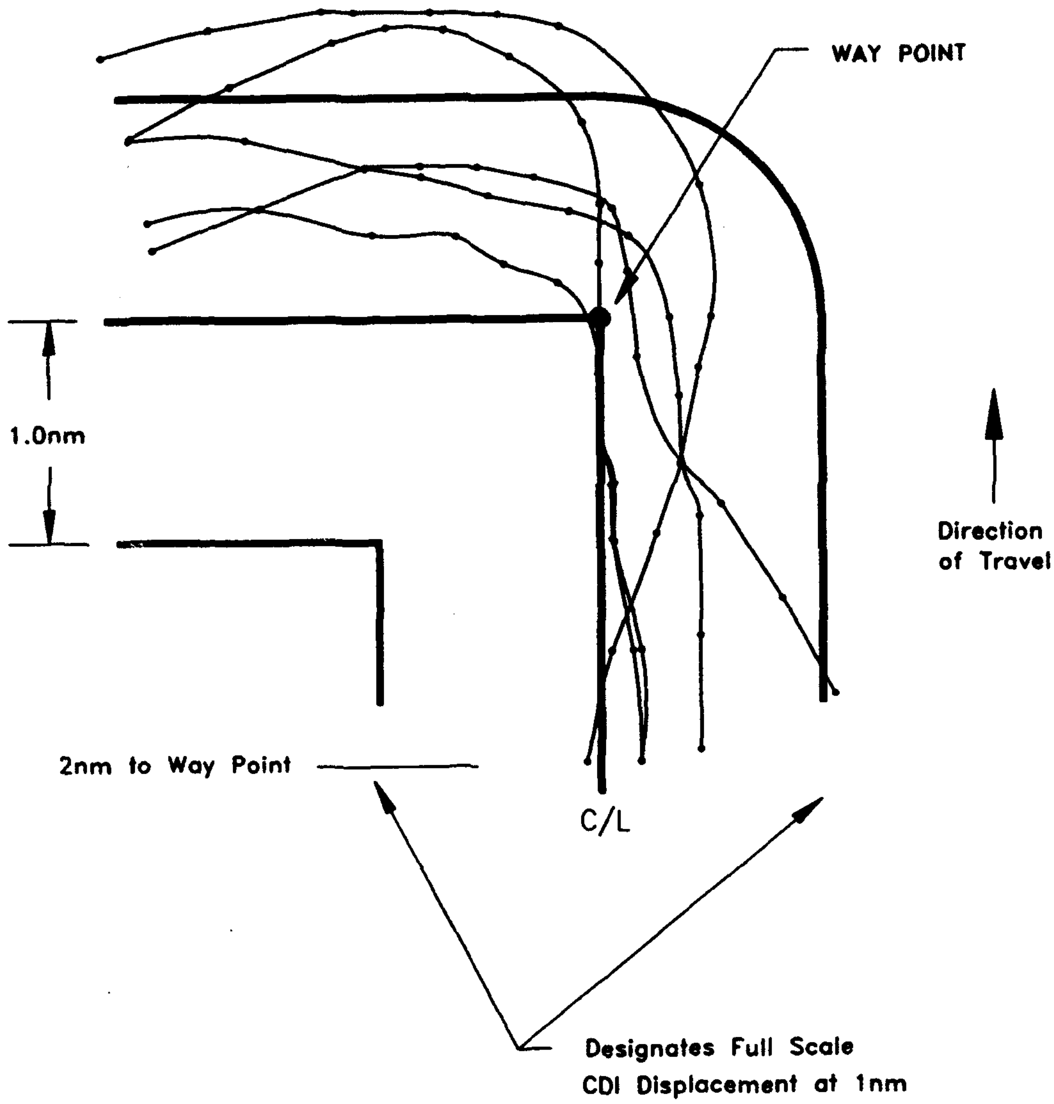

Figure 17. Five ground tracks made by one pilot who initiated the 90 degree turns at or beyond the waypoint during the missed approach procedure

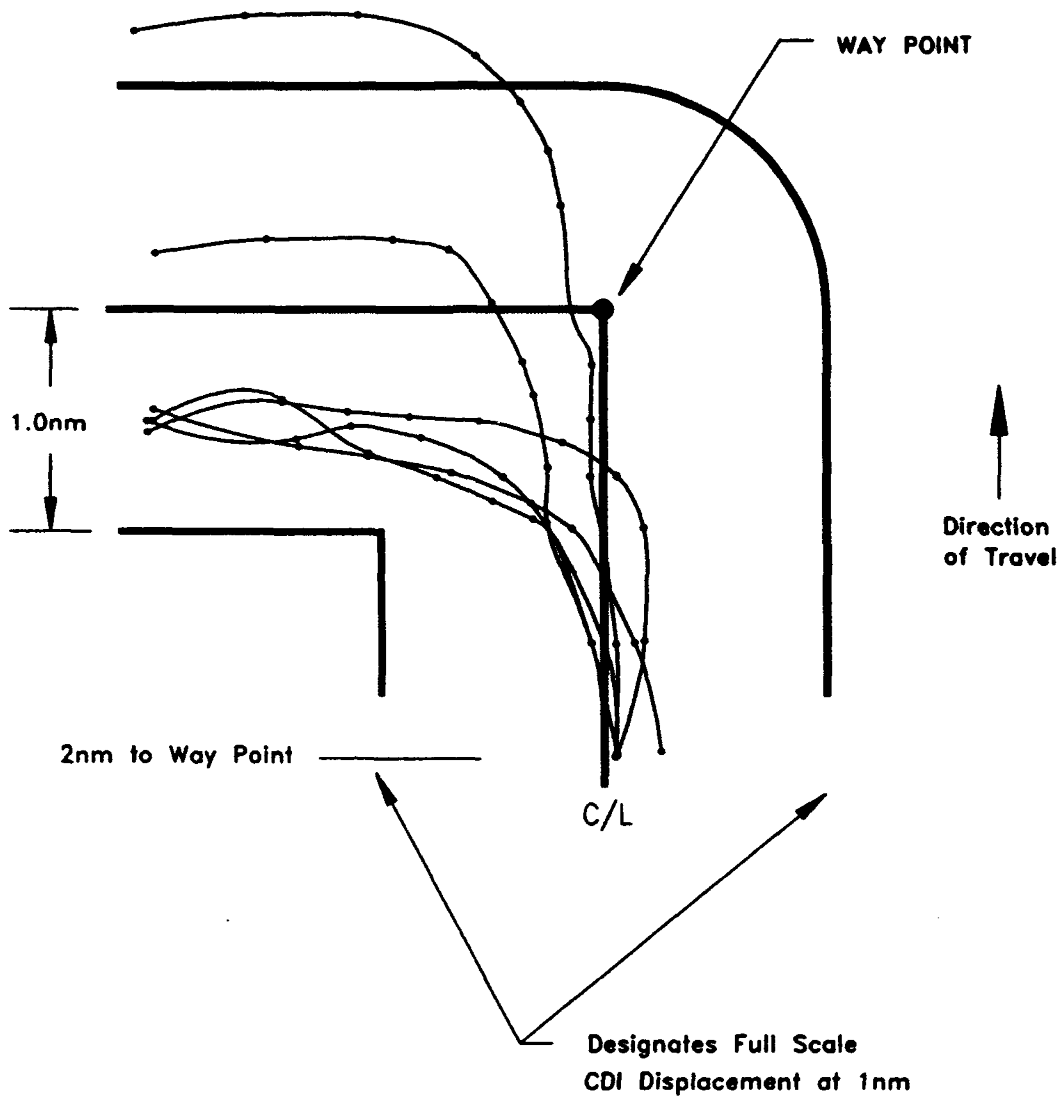

Figure 18. Six ground tracks made by one pilot who initiated most of the 90 degree turns at or before the waypoint during the missed approach procedure

procedure and failed to notice the distance of the upcoming waypoint or because he was waiting for the GPS to advance to the next waypoint and provide guidance for the new heading. Figure 18 illustrates the tracks of a pilot who anticipated most of the turns sufficiently well to stay close to the course centerline on the majority of his flights. Clearly, the path width required to contain all tracks could be narrowed considerably if the receiver were configured to display turn anticipation and the pilots flew as directed.

All pilots were instructed to fly by, rather than over, all waypoints other than the missed approach waypoint. In order to do this, the pilots had to ignore the CDI indications as they turned before reaching the various waypoints. Examination of some of the ground tracks indicates that they did not always ignore the CDI as directed, and may not be expected to do so. The ground track shown in Figure 19 illustrates one such case.

Figure 19 illustrates a case where the GPS receiver was late in switching to the hold waypoint. The switch should have occurred before or at the indicated waypoint. The ground track indicates that the pilot started to initiate the turn before the illustrated waypoint but did not fully commit himself to it until the switch to the next waypoint occurred.

Selective Availability

DOD guarantees that SA will be within 100 meters 95 percent of the time. This 100 meters may be added to FTE as a worst case estimate of the influence of SA on system error and may be considered in determining whether flights using GPS navigation can be contained within TERPS designed for non-precision approaches, even though 100 meters is less than 0.054 nm and has little practical influence on the utility of GPS for flying NDB and VOR non-precision approaches.

In order to determine if 100 meters was a realistic value, measures of the difference in position solutions between a known location and nondifferential GPS positions estimates were taken at the Volpe Center concurrently with most of our data collection approaches. The Volpe Center is located within 45 nm of Gardner airport where the flight testing was conducted.

Figure 20 shows a distribution of SA-induced error for one approach. The size of the SA error is shown in meters on the horizontal axis, and the number of one-second samples that recorded an error of this magnitude is indicated on the vertical axis. The errors represented by this histogram were recorded during the 2.5 minutes of a single (rather slow) final approach. During this approach the error ranged from 22 to 29 meters and were between 22 and 25 meters for the most part.

Figure 21 shows a 24-hour sample of SA-induced errors. It may be seen here that although the vast majority of errors are less than 100 meters, errors as large as 242 meters (0.13 nm) did occur. We used the 100 m (95 percent) as the navigation signal and receiver components of the non-differential GPS system error in determining if the non-differential GPS systems error falls within the area covered by the off-site VOR TERPS.

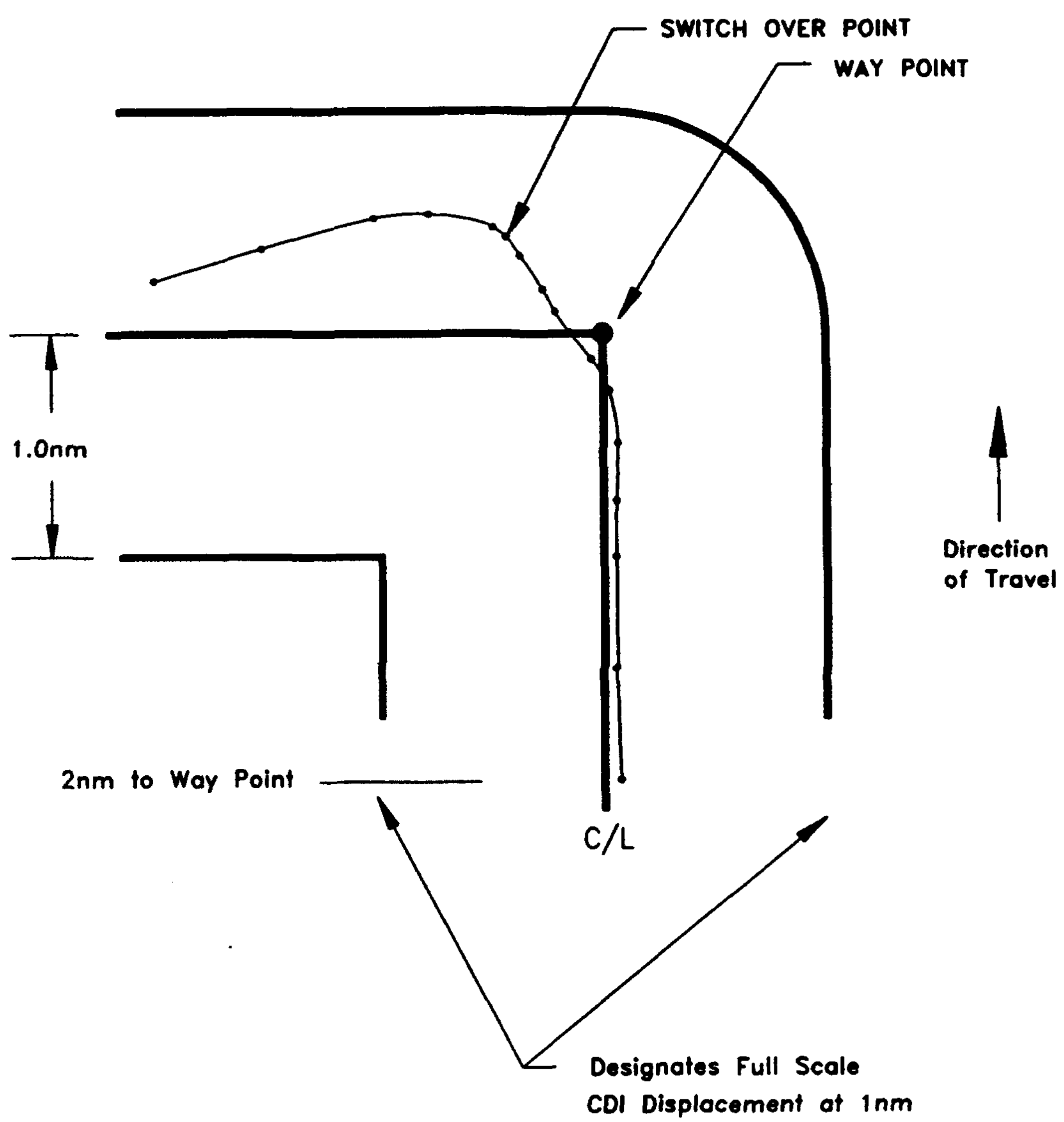

Figure 19. A single ground track made by one pilot executing a 90 degree turn during a missed approach procedure. The track illustrates the influence of CDI indication on the pilot's willingness to execute the turn without positive course guidance.

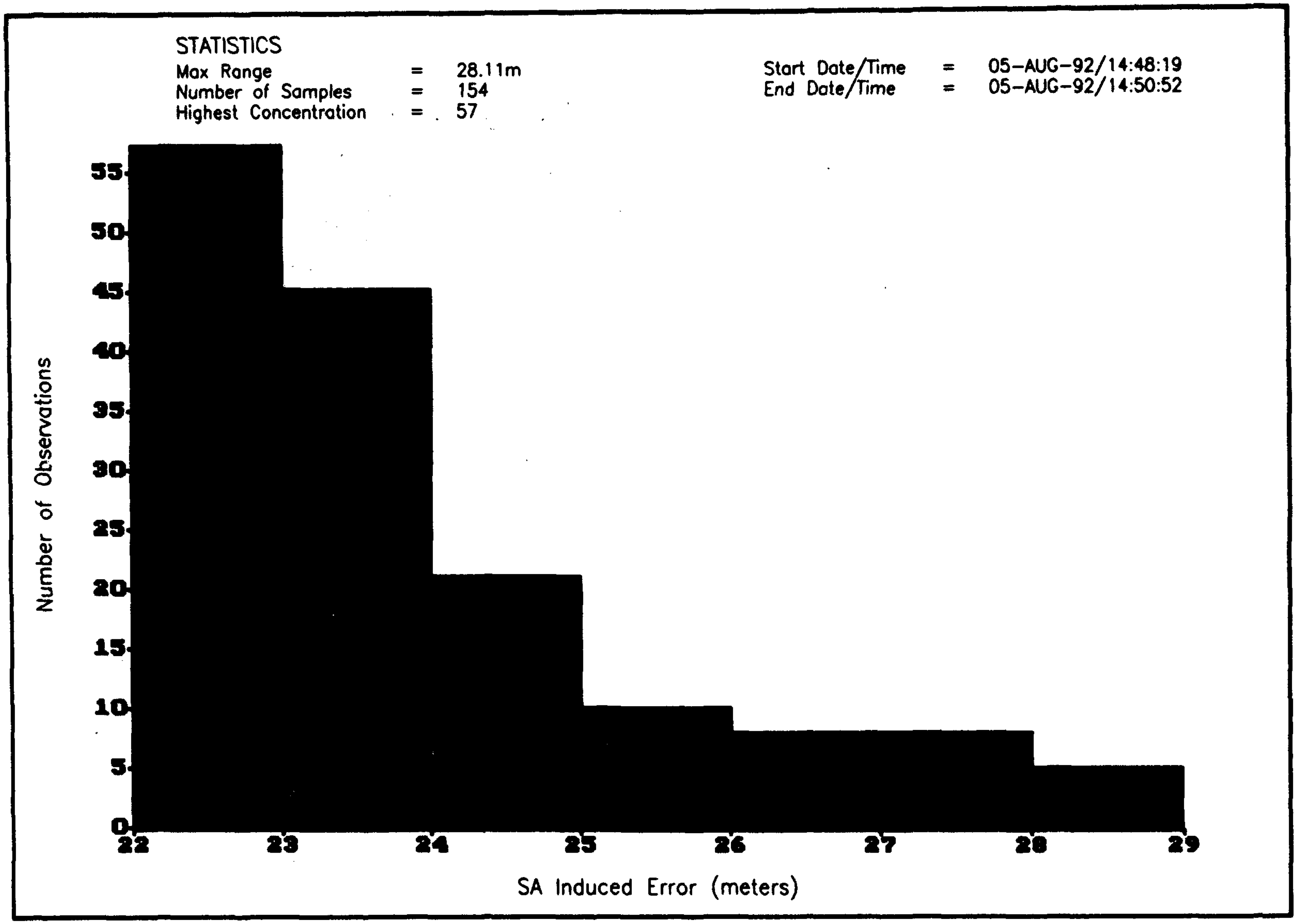

Figure 20. Magnitude of SA error by frequency of occurrence for observations made once per second during a final approach

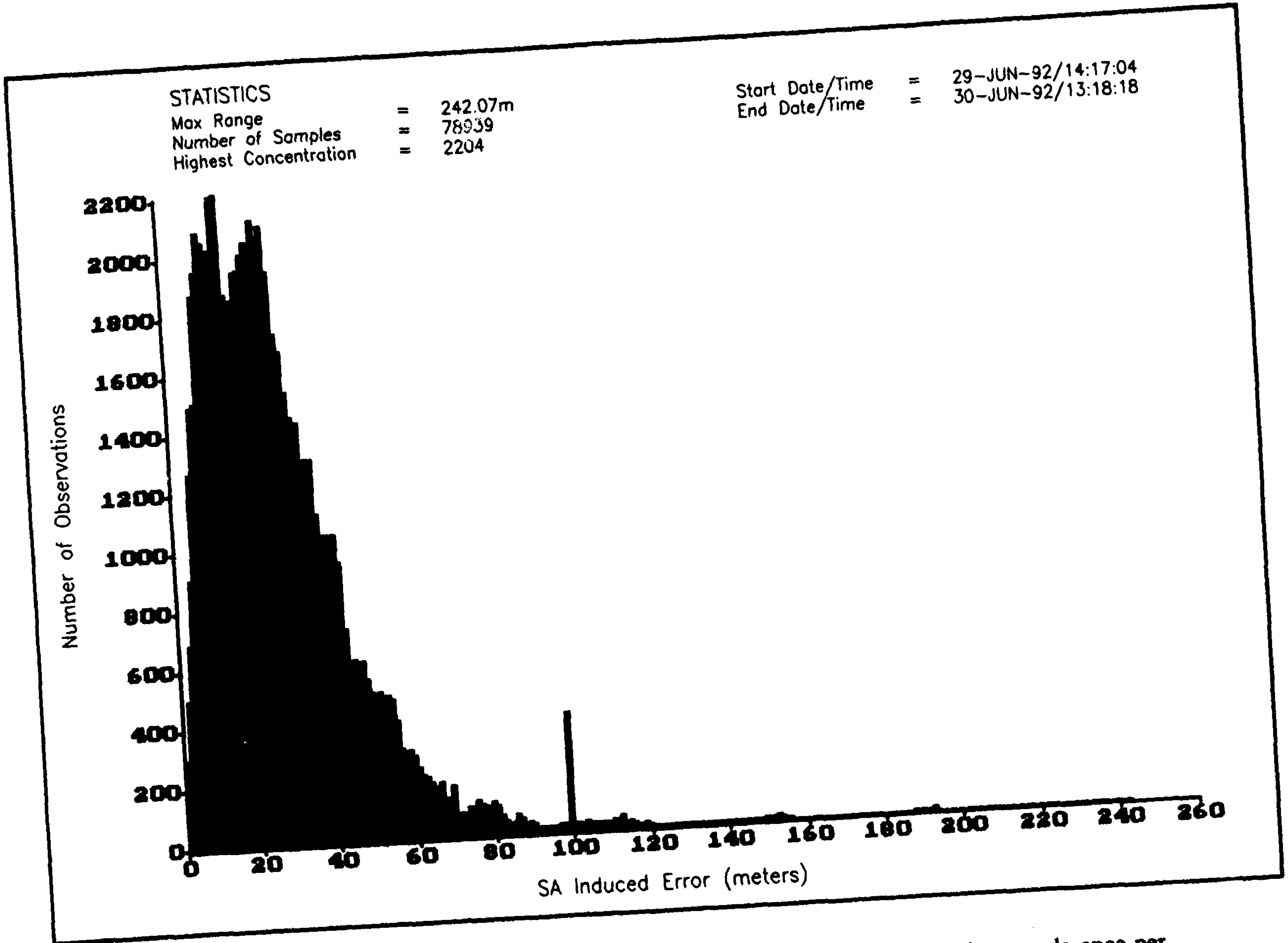

Figure 21. Magnitude of SA error by frequency of occurrence for observations made once per second during one twenty hour period

Pilot Workload

Spare Attention

Two estimates of pilot workload were used in this evaluation. We asked each pilot during morning and afternoon data collection sessions to indicate on a 10 point Bedford-type workload scale (Figure 3) how much spare attention he had while flying the GPS procedure. Following the completion of the data collection approaches, we asked each pilot to compare the difficulty of the GPS approaches to similar VOR and NDB approaches.

The responses to the Bedford scale are summarized in Table 9. As expected, the pilots found the procedures easier to fly in the afternoon than the morning. Ten out of the 12 pilots felt that they had enough spare time while flying to adequately attend to additional tasks even during their earliest approaches. One pilot reported that when the procedures were initially flown he had barely enough time to attend to anything other than primary flight tasks (8). After several approaches, this pilot felt that he had enough spare attention while flying to easily attend to additional tasks (2). The average response both in the morning and afternoon indicated that most pilots felt that there was more than ample spare time to attend to other tasks while flying the approaches.

Table 9. Morning and afternoon workload estimates made by twelve pilots on the 10-point workload scale

Pilot	Morning	Afternoon
1	1	2
2	3	2
3	5	4
4	8	2
5	2	1
6	2	2
7	1	4
8	5	1
9	3	2
10	6	2
11	3	3
12	3	2
$\bar{x}$	3.5	2.3

Comparison with VOR and NDB Approaches

The pilots were asked to compare the effort and difficulty of flying the GPS approaches with a comparable VOR or NDB approach. This question placed GPS at a considerable disadvantage because the approach procedure that we used in these tests was nearly the most difficult configuration permitted by VOR TERPS. Most likely, the VOR and NDB approaches that the pilots mentally compared to our approaches were much easier. The relative difficulty of our procedure was due to the incorporation of 120 degree and 30 degree turns, high descent rate on final, and the close proximity of waypoints that had to be continuously monitored. The pilots had to remember or reference the approach plate frequently to determine heading changes and to relate the waypoint names they saw on the receiver display to their location on the approach procedure chart. These requirements for repeated reference to the approach plate and close monitoring of the GPS receiver display (it was not mounted in an optimal location) and the aircraft's primary flight instruments, forced a much broader scan pattern than is normally used during an instrument approach. Nevertheless, as can be seen in Tables 10 and 11, at least two thirds of the pilots reported that navigation and manual flight control was as easy or easier on GPS approaches than on VOR or NDB approaches.

At least two features of the GPS system could make GPS-defined approaches relatively easy. First, GPS provided the pilot with continuous distance-to-waypoint information, and second, the sensitivity of the GPS CDI was constant from the final approach fix to the missed approach point.

Table 10. Number of pilots who selected particular responses when comparing GPS with VOR approaches

		COMPARISON OF GPS WITH VOR					
	NAVIGATION				MANUAL FLIGHT PATH CONTROL		
	Mental Effort					Mental Effort	
	Much	1				Much	0
MORE	Moderately	1			MORE	Moderately	2
	Slightly	2				Slightly	1
	Same	2				Same	3
	Slightly	1				Slightly	2
LESS	Moderately	3			LESS	Moderately	2
	Much	2				Much	2
	Time Required					Physical Difficulty	
	Much	0				Much	0
MORE	Moderately	1			MORE	Moderately	0
	Slightly	3				Slightly	3
	Same	2				Same	5
	Slightly	3				Slightly	1
LESS	Moderately	2			LESS	Moderately	2
	Much	1				Much	1
	Understanding of Horizontal Position						
		Much	0				
MORE DIFFICULT		Moderately	3				
		Slightly	1				
		Same	2				
		Slightly	0				
LESS DIFFICULT		Moderately	2				
		Much	4				

Table 11. Number of pilots who selected particular responses when comparing GPS with NDB approaches

		COMPARISON OF GPS WITH NDB					
	NAVIGATION				MANUAL FLIGHT PATH CONTROL		
	Mental Effort					Mental Effort	
	Much	1				Much	0
MORE	Moderately	0			MORE	Moderately	1
	Slightly	2				Slightly	0
	Same	0				Same	2
	Slightly	1				Slightly	4
LESS	Moderately	2			LESS	Moderately	0
	Much	6				Much	5
	Time Required					Physical Difficulty	
	Much	0				Much	0
MORE	Moderately	0			MORE	Moderately	0
	Slightly	1				Slightly	0
	Same	4				Same	5
	Slightly	1				Slightly	1
LESS	Moderately	2			LESS	Moderately	2
	Much	4				Much	4
	Understanding of Horizontal Position						
		Much	1				
MORE DIFFICULT		Moderately	1				
		Slightly	1				
		Same	1				
		Slightly	0				
LESS DIFFICULT		Moderately	3				
		Much	5				

5. CONCLUSIONS

CDI Sensitivities

The terminal and approach CDI sensitivities specified in TSO-C129 were determined to be flyable for the following reasons:

(1) The probability of a full-scale deflection during all parts of the approach procedure where CDI sensitivity was set at 1 nm full scale is less than 0.05.

(2) The probability of a full-scale deflection during the last 4 miles of the 5 mile final approach course when a 30 degree turn is made at the FAF following a 10 mile intermediate segment is less than 0.05 when the CDI sensitivity is set at 0.30 nm, full scale.

(3) The probability of a full-scale deflection during the full final approach following a 2 mile intermediate segment in line with the final approach course is less than 0.05 when the CDI sensitivity is set at 0.30 nm, full scale.

(4) Most pilots report that flying a GPS non-precision approach is as easy or easier than flying a comparable VOR or NDB approach.

(5) On average, pilots report that flying a GPS approach is a relatively light workload task, i.e., they report having spare attention available for other tasks while flying an especially difficult GPS non-precision approach.

VOR TERPS

The TERPS currently designed for off-site VOR approaches are more than adequate to provide obstacle-free protection for GPS non-precision approaches.

Figure 22 depicts the TERPS criteria for non-precision approach using an off-site VOR and system error values calculated for GPS at the IAF, IF, and MAP. The trapezoids indicated by the lines on the outside of the figure represent the extent of total system error for VORs. The trapezoids drawn with dashed lines represent GPS system error. This error is estimated to be 1.11 nm to the left and right of the IF, considerably less than the 2 nm allowed for a VOR approach. This number was derived by adding the 100 meter (0.054 nm) SA error to the 0.95 probability value (1.06) shown in Table 2 for a 120 degree turn. The FTE values used in these calculations are worst case values. For example, as the value in the column left of the mean in Table 2 was worse than the one to the right, the former was used.

The 0.394 nm value shown at the FAF was obtained by adding the SA error (0.054) to the 0.95 probability value shown at the 30 degree turn in Table 2.

The 0.164 value representing systems error at the MAP was obtained by adding the SA error (0.054) to the 0.95 probability value shown for Section 6 in Table 2.

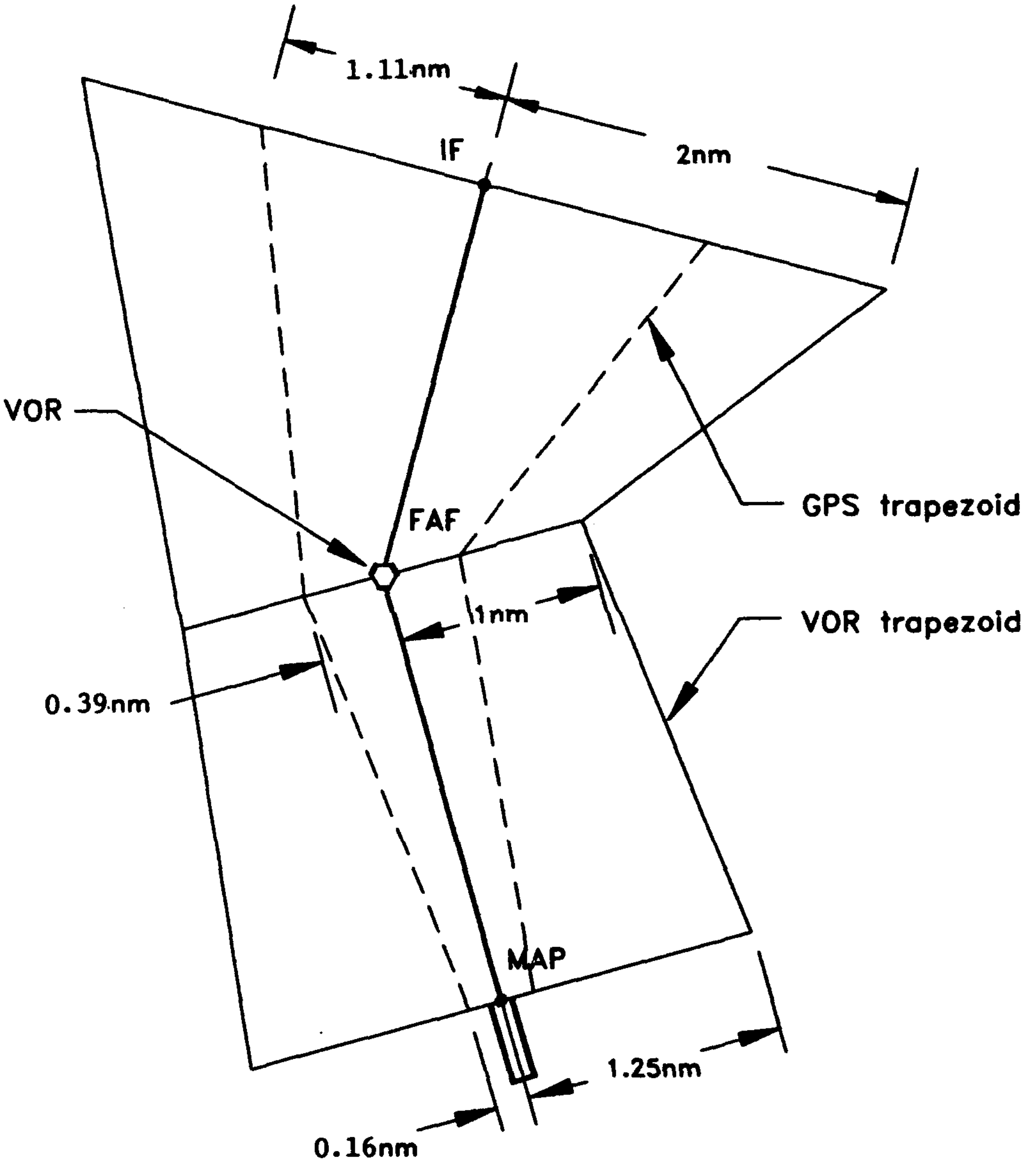

Figure 22. Trapezoids representing total system error for off-site VOR and 95 percent FTE plus 100 meters for GPS

Clearly, nondifferential GPS system error falls well within the TERPS boundaries specified for off-site VOR approaches.

Localizer TERPS

Figure 23 depicts the TERPS criteria for a non-precision approach using a localizer and system error values calculated for GPS at the IAF, IF, and MAP. The trapezoids indicated by the lines on the outside of the figure represent the extent of total system error for a localizer. The trapezoids drawn with dashed lines represent GPS system error as they do in Figure 22. This error is estimated to be 0.39 nm to the left and right of the outer marker, considerably less than the 0.83 nm allowed for a localizer approach. But GPS system error falls outside the localizer primary area near the threshold. The localizer TERPS specify that the half width of the localizer primary area be 500 ft, 1000 ft from the threshold, about one half the width of the GPS trapezoid at this point. The nondifferential GPS system error trapezoids go outside the localizer trapezoid area about one half-mile before the threshold.

It is likely that if a CDI that increased in sensitivity were used, as does a localizer needle, it would produce FTE performance that would be contained within the localizer trapezoid. Flight testing should be accomplished to verify this assumption.

Performance during Missed Approaches

Performance during the missed approaches was not as good as on final approach, probably because of the need to attend to cleaning up the aircraft and the relative importance of airspeed and altitude control. The implication of this result is that the CDI sensitivity that is optimal for executing a missed approach will be less than that used for a final approach, and that broader obstruction-free areas may be required for missed approach procedures than for the same maneuvers when required before the missed approach point.

Missed approach procedures may be expected to become more complex as GPS navigation becomes increasingly integrated into the NAS. The independence of GPS from ground-based transmitters means that many remote airports that could not have instrumented approaches because of surrounding terrain may now have them. However, because of that terrain, missed approach procedures may have to be more complex and their execution more precise. It may be necessary for some missed approach courses to involve several turns in close proximity to one another as well as requiring adherence to a multistep vertical profile during climbout. Because little is known about the ability of pilots to execute complex maneuvers during missed approaches, considerable research must be done to support the development of missed approach TERPS for GPS instrument procedures. Minimum segment length, turn angles, climb rate requirements and interactions among these variables must all be determined empirically.

Comparability to Category A Data

The comparability of FTE data collected in Category A and Category B approaches affirms the wisdom of using a CDI sensitivity of 0.30 nm on final approach. It doubles the data

supporting this value and permits and extends the results of the present study to conditions involving lighter aircraft and slower approach speeds.

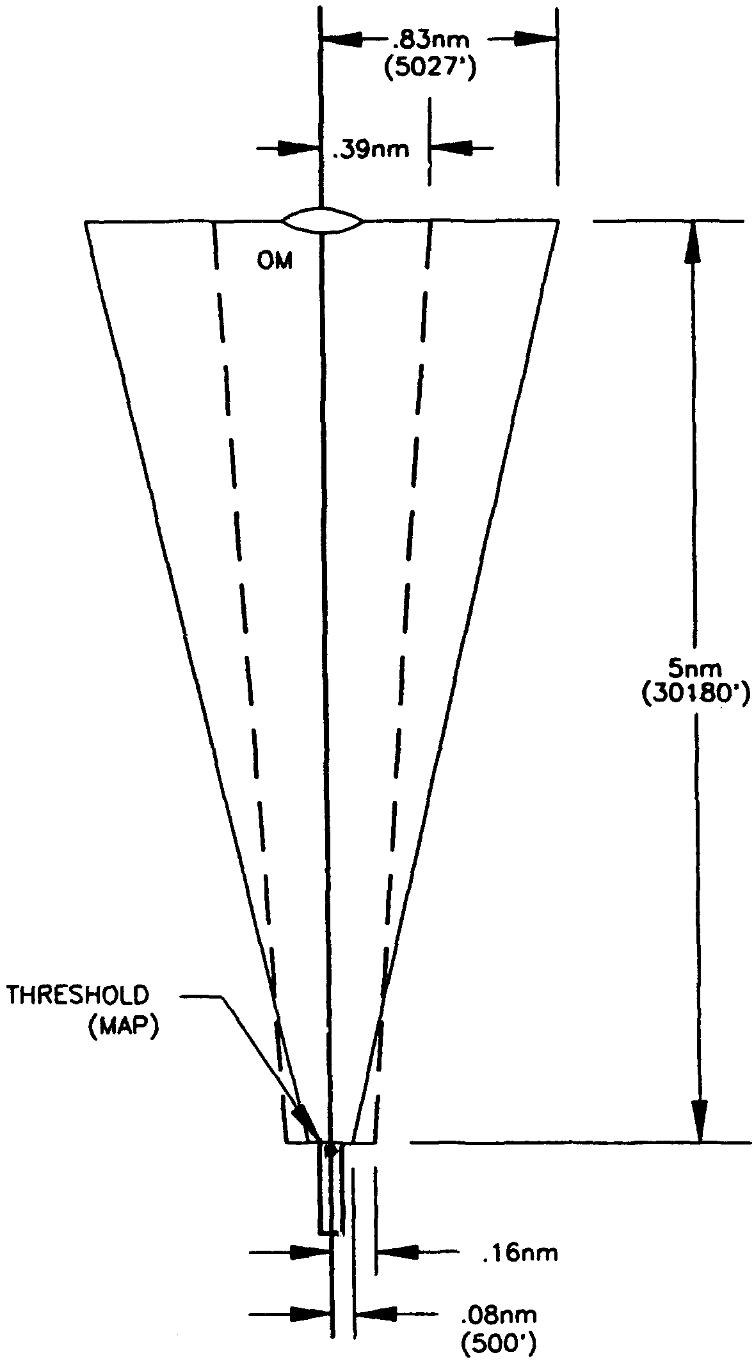

Figure 23. Trapezoids representing total system error for localizer non-precision approach and 95 percent FTE plus 100 meters for GPS

6. DISCUSSION

6.1 PROCEDURES

The procedures that were flown in this study were the worst-case procedures that are currently permitted by VOR TERPS. The most difficult aspect of them was the 120 degree turn followed by 30 degree turn over the FAF, followed by a 380 feet per mile descent rate to the MAP. The pilots flew the procedure without too much trouble, but they were clearly kept busy and some reported uncertainty with regard to where they were in the procedure. Similar reports have been made by Air Force pilots flying GPS procedures with Cat D aircraft. Multiple headings and waypoints including the 120 degree turn required the pilots to reference their charts frequently, sometimes while they were dead reckoning through turns. This increased head down time and reduced the time available for tracking.

6.2 LENGTH OF INTERMEDIATE SEGMENT

Current VOR TERPS require a 10 nautical mile intermediate segment following a 120 degree turn. GPS TERPS remain to be determined, but it is clear from our results that many pilots require more than a five mile segment to become stabilized following a 120 degree turn.

Discussions with procedure specialists indicate that 120 degree turns would never be required for a GPS procedure. The option of being able to present a waypoint wherever needed gives procedure specialists more freedom in designing procedures than was available when the characteristics of the procedure were determined by the location of a ground-based beacon. A new, more relevant concern may be the minimum length of segments that should be used to link consecutive turns of 15 to 30 degrees.

The more segments that are used, the more the pilot must reference the chart and distance-to-waypoint display to fly the procedure. Short segments will give the pilot little time to determine when to initiate turns to new segments and to determine which heading will keep him or her on that segment. In the current study, the pilot had to scan well beyond the primary flight instruments to determine the distance to the next waypoint and the name of the active waypoint from the GPS display. The name of the next waypoint and the track to it had to be determined from the chart. NOS style charts were used in the current study. The small size of the alphanumerics used with these charts made them difficult to use, particularly as repeated reference was required to fly the procedure. Flight technical error will be reduced and situational awareness increased if distance information is presented in the pilots' primary area of view, and the plan view on GPS charts is more easily read than is currently the case.

The ground track data indicate that pilots may not be too concerned about having the CDI centered as long as it is alive and near the center. The CDI sensitivity change from 1 nm to 0.30 nm just before the FAF clearly induced the pilots to attend more to the tracking performance. Ground tracks of performance on final approach and the tabulated FTE data showed definite improvement in tracking as the pilots proceeded from the FAF to the MAP. It is entirely likely that further improvements could be achieved with minimal increases in workload if a localizer-like sensitivity profile were used with the CDI, so that CDI sensitivity increases with decreasing distance from the MAP.

When all ground tracks throughout the 90 degree turn in the missed approach procedure were shown, considerable spread was evident. However, when the consecutive tracks of single pilots were shown, it appeared that the spread was at least partially due to the strategy that the individual pilots used for initiating the turn. Pilots who turned at the waypoint flew beyond it on the turn and those who turned before the waypoint tended to turn inside that waypoint. Some GPS receivers have turn anticipation, that is, based upon the aircraft's calculated ground speed, the receiver "tells" the pilot when to initiate the turn. The receiver that was used in this study had this capability, but it was not exercised. If it had been, the distribution of tracks through the turns would have been narrower.

Alternatively, if the pilot had been told how far from the waypoint to initiate the turns, group performance would have been improved. Clearly, focused training on executing turns could yield similar improvements.

The current research was conducted to determine if pilots using GPS guidance for flying non-precision approaches could stay within areas defined by TERPS designed for off-site VOR procedures. The present research demonstrated that they can, even with charts and displays that were not well designed for the task. However, it also demonstrated that there is a strong likelihood that performance can be improved through some rather simple changes in display and perhaps chart design. The magnitude of the improvements that can be readily achieved is not known, nor are the limits of pilots' capabilities for flying approaches that could be designed specifically for GPS.

Future research should be conducted to support the implementation of GPS into the NAS as the primary system for air navigation. The following list was made of research requirements deemed necessary to facilitate that implementation.

6.3 REQUIREMENTS FOR RESEARCH

The independence of the location of GPS waypoints from terrain characteristics and possibility of continuous and precise vertical guidance means that within the forseeable future, the options available to air traffic controllers for handling aircraft will be vastly increased; similarly the designers of terminal and approach procedures will have more options. Potential constraints to the design and use of waypoint-defined instrument approach and departure procedures are limits in the ability of pilots to fly them.

The influence on FTE of having to select waypoints using the controls of the receiver while flying are not known. The full approach and missed approach required for the procedures tested in this study were preprogrammed as they would be in a receiver certified in accordance with TSO C129. The pilot was not required to use the controls of the receiver during the approach or the miss because the receiver automatically sequenced through the waypoints defining the procedure. However, when GPS navigation becomes a mature system and ATC has learned to take advantage of its capabilities, pilots will be required to tune in five-letter waypoints while flying in congested airspace. Terminal operations will change and terminal area navigation will become more precise and more highly structured, even for operations conducted under VFR. For example, it may be expected that air traffic control will direct aircraft with vectors much less frequently than at present. Terminal areas will be

designed with a constellation of waypoints that will allow air traffic control to direct aircraft to any point or sequence of points in that constellation with the knowledge that the resulting positive course guidance will reduce the unreliable influences of wind effects and misaligned directional gyros on the ground track of the aircraft. Almost all navigation in the terminal area will be with positive course guidance. With the anticipated increase in the number of terminal area operations by the next decade, it may be expected that ATC will need the freedom to decrease aircraft separation in these areas. Probably, unpublished missed approach procedures will be direct to waypoints or sequences of waypoints, even at uncontrolled fields. Even under VFR conditions traffic patterns will be defined by waypoints rather than subject to the distance judgment variations of individual pilots. In this application, VFR as well as IFR pilots would require terminal area charts to illustrate the location and names of the relevant waypoints. Conceivably, different sets of waypoints will be used with different categories of aircraft to optimize use of terminal airspace and ensure separation of IFR and VFR traffic.

These possibilities in the design of terminal operations raise the following questions that should be under investigation:

CDI sensitivity

Research has shown that FTE can be reduced by increasing CDI sensitivity, but that this is accomplished at the cost of increased workload and reductions in attention to other flying tasks. How should CDI sensitivity be varied to accommodate requirements for flying precision and acceptable levels of workload? No work has been done on the influence of the sensitivity of the horizontal and vertical CDIs on the pilots ability to track an altitude profile during climbout on a missed approach.

Missed approach procedures

What differences will there be in FTE while flying published (preprogrammed) and ATC directed (programming while flying) missed approaches? Research to date that has determined how accurately pilots can fly GPS-defined approach procedures has used preprogrammed approach procedures that eliminate the need for pilots to use the controls of the receivers while flying in the terminal area. During missed approaches when ATC directs the pilot to a waypoint not included in the published missed approach, the pilot will have to program in the new waypoint using a five-letter identifier. The extent of this distraction on pilot tracking and altitude control should be determined.

Some airports that currently lack instrument approaches because of terrain features or cost of ground based equipment may soon have them, as intricate approach and missed approach procedures may be required for these airports. Because of the proximity and arrangement of obstacles to the runway, some of these may require vertical positive guidance for the missed approach procedure. The influence of the missed approach procedure on FTE during missed approaches with and without continuous vertical guidance should be known by procedures specialists. Investigations should include procedures defined by multiple waypoints, profile climbouts, and those requiring immediate course reversals.

Chart design

Terminal area charts will become more important than they have been in the past. The creation of constellations of waypoints in the terminal area will create new problems in chart design. Special symbols for representing waypoints with different applications may have to be created to facilitate chart readability. Because of the increased clutter and possibly the necessity for accurately initiating turns to upcoming waypoints in the absence of ATC vectors, course headings should be depicted much more clearly than is presently the case.

VFR charts

Charts for depicting terminal area waypoints to be used for VFR operations also must be redesigned. These charts must be improved to minimize head-down time required for their use because they may be used under VMC in traffic not under ATC control. Ease of use of GPS equipment is particularly important for VFR pilots, since they may not be experienced or well trained in the use of complex navigation systems in face of the stress and congestion of terminal area operations.

Situational awareness

Some pilots using Loran/GPS waypoints for navigation in terminal areas report are reporting the need for map displays. They say that determining present position with regard to multiple waypoints is more difficult than locating themselves with reference to a single NAVAID such as a VOR or NDB. This uncertainty causes them to depend more on their charts than is otherwise the case. This problem will be increased as the number of waypoints used in terminal areas is increased. Research is needed to examine and evaluate different formats that could be used with moving map displays.

Fatigue and display design

One advantage of the greater precision in navigation provided by GPS guidance is the ability to position aircraft more closely together in the terminal area and to help pilots to fly instrument approaches more accurately. Spacing and obstruction clearance requirements with GPS are based upon the accuracy with which pilots can fly terminal procedures. The conditions under which these determinations are made influence the usability of the information derived from them.

With mounting pressures to increase terminal area productivity, it is becoming more important to understand the influences of the pilot's physiological state and the design of controls and display on the precision of aircraft handling. Current certification guidelines permit instruments that must be monitored continuously for some instrument approaches to be separated by sufficient distance in the cockpit to ensure that the pilot scans the major portion of the total instrument panel during high workload approach activities. Fatigue resulting from demanding flight schedules and environmental conditions such as weather is an important and common problem in many cockpits. It is well known that stressors such as fatigue reduce the human operator's ability to time-share and integrate information that must be obtained from separated data sources. Research is required to determine the influence of fatigue on flight

technical error and the effects of display design on those influences.